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SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

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STRUCTURAL DESIGN CRITERIA APPLICABLE TO A SPACE SHUTTLE

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PREFACE

In 1969, when planning for the development of a manned space-shuttle vehicle began, it was evident that significant advances in structural design would be needed to combine a manned recoverable booster and a reusable orbital vehicle with conventional flight and landing capabilities. Accordingly, new structural design criteria would be required for use in the vehicle development program to obtain a flightworthy structure (i.e., a structure possessing sufficient strength and stiffness and all other physical, mechanical, and functional characteristics required to accomplish each vehicle mission without jeopardizing mission objectives).

Early in 1970, the National Aeronautics and Space Administration initiated a program to prepare structural design criteria applicable to a manned space-shuttle vehicle. This document presents the first efforts of that program.

The work was conducted by a committee formed from representatives of major aerospace companies with an interest in the space shuttle. The material prepared by the committee was reviewed by a NASA evaluation team composed of personnel from most NASA centers and from NASA headquarters who are experienced in structural engineering technology. Liaison was provided by the United States Air Force.

Meetings of industry, NASA, and liaison members were arranged; at these meetings, problem areas were discussed, guidelines established, and tasks assigned. Individual contributions were prepared by industry members between meetings. The entire document was reviewed and comments on the document were obtained from members for review by the NASA evaluation team and the USAF liaison. The activity was managed and the document was edited by the Langley Space Vehicle Design Criteria Office.

The structural criteria presented in this document are limited to general and mission-oriented criteria since specific configurations have not yet been developed. Care has been taken to ensure that the criteria will not restrict configuration development and will not establish the overall risk level. In some instances, margins of confidence are indicated, not only because experience has shown them to be necessary but also because technology now permits quantitative values to be established. Some of the criteria are supplemented by interpretations, guidelines, and discussion. Consequently, the criteria do not represent structural requirements, structural specifications, or any type of contractual document, but rather are intended to assist in the preparation of such documents.

There are a number of important structural criteria problem areas which have been identified as a result of this activity. A summary of these problem areas, together with suggested study programs, has been submitted separately to NASA. If some or all of these studies are conducted, it is expected that the results will provide additional criteria definition for a revision of this document at some future date. A revision is also considered appropriate when configurational data and additional mission details from the Phase B vehicle studies become available.

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CONTENTS

1. INTRODUCTION

1.1 PURPOSE

This document is applicable to a manned space-shuttle mission but not specifically applicable to any single configuration. The information results from the experience of industry and NASA in the design, development, and operation of aircraft and space vehicles; it is intended to provide a starting point for preparation of meaningful requirements and specifications. An early understanding between the hardware contractor and NASA as to what is required to produce flightworthy space-shuttle structures should increase confidence that critical problem areas are not being overlooked. In addition, in the process of developing this document, problem areas requiring further research have been identified (to be described in a separate document), and current research can now be viewed in terms of its applicability to space-shuttle vehicles.

1.2 SCOPE

This document presents structural design criteria and interpretive information for the structural design of an earth-to-orbit space-shuttle vehicle in all configurations (i.e., vehicles mated in the launch configuration or unmated, as during entry or ferry). These criteria and supporting information apply to all phases of the shuttle life, independent of external vehicle configuration. Included herein are the following:

- Design objectives
- Design characteristics
- Design conditions
- Natural and man-made environments
- Proof of design.

1.3 APPROACH

In this document, statements in bold-faced type are design criteria and statements in ordinary type provide guidance for interpretation of the criteria. Related documents drawn from structural design criteria experience with aircraft, spacecraft, and launch vehicles are listed in Section 2.

The design objectives are presented in Section 3 to ensure that development of mission objectives is consistent with the technological capabilities of structural design, and to serve as a basis for the continuing development of rational structural design criteria. However, the objectives in Section 3 are subject to change as additional space-shuttle tradeoff studies are performed.

Section 4 defines the structural characteristics that the space-shuttle vehicle shall exhibit to provide sufficient strength and stiffness under all expected service environments, including conditions imposed by its systems, and to enable the shuttle to function mechanically.

Section 5 defines the phenomena, events, environments, and hazards that shall be accounted for in the various phases of the vehicle's service life.

Section 6 describes the natural and man-made environments applicable to the structural design of the space shuttle.

Section 7 defines the procedures which shall be performed and documented to demonstrate the structural adequacy of the space shuttle. This section also defines the measurements to be taken during vehicle operation.

1.4 APPLICATION

This document applies to the design of all structural components of all earth-to-orbit space-shuttle vehicles. In addition, the criteria apply to characteristics of materials and functional systems, including propulsion systems, to ensure their structural adequacy and compatibility.

1.5 PRECEDENCE

In the event of conflict between information in this document and in the contract specifications, the information in the specifications shall take precedence.

Values and factors stated herein are to be regarded as "starting points" for generating structural design requirements for space-shuttle programs.

1.6 DEFINITIONS

For purposes of this document, the following definitions should be used.

ABORT. A termination of a mission due to malfunction or failure.

ASCENT. (See Life Phases)

ASSEMBLY. A combination of two or more components that function as a discrete element of a system. (See Component and System)

ATMOSPHERIC FLIGHT. (See Life Phases)

BUFFET. A repeated loading of a structure by an unsteady aerodynamic flow.

BUZZ. A control-surface phenomenon; a type of flutter including only one degree of freedom. Buzz is usually a pure rotational oscillation of a control surface, but may appear as a torsional "windup" oscillation if the surface is restrained near one end. It generally occurs in regions of transonic flow.

COMPONENT. A separate element, member, or part of an assembly. (See Assembly and System)

CONDITION. A phenomenon, event, time interval, or combination thereof to which the space vehicle is exposed. (See Design Condition)

CONTROL EFFECTIVENESS. The control moment per unit of control deflection. It is affected by structural deformation caused by the reaction to the control force.

CREEP. A time-dependent deformation under load and thermal environments which results in cumulative, permanent deformation.

CRITICAL. The extreme value of a load or stress, or the most severe environmental condition imposed on a structure during its service life. The design of the structure is based on an appropriate combination of such critical loads, stresses, and conditions.

CRYOGENIC TEMPERATURE. A temperature below about -100°C.

DESIGN CONDITION. A condition important in structural design and which may involve a specific point in time or integrated effects over a period of time in terms of physical units such as pressure, temperature, load, acceleration, attitude, rate, flux, etc. (See Condition)

DETERMINISTIC. Denotes that values used in design are discrete and not random. Deterministic values are determined on the basis of available information and experience. (See Probabilistic)

DETRIMENTAL DEFORMATIONS. Structural deformations, deflections, or displacements which (1) cause unintentional contact, misalignment, or divergence between adjacent components; (2) cause a component to exceed the dynamic space envelope established for that component; (3) reduce the strength or rated life of the structure below specified levels; (4) degrade the effectiveness of thermal protection coatings or shields; (5) jeopardize the proper functioning of equipment; (6) endanger personnel; (7) degrade the aerodynamic or functional characteristics of the vehicle; (8) reduce confidence below acceptable levels in the ability to ensure flightworthiness by use of established analytical or test techniques; or (9) induce leakage above specified rates.

DIVERGENCE. A nonoscillatory instability which occurs when the external aerodynamic upsetting moments exceed the internal structural restoring moments within a system.

ELASTIC MODE. Same as Vibration Mode.

EMERGENCY CONDITION. A loading, temperature, event, or combination thereof which exceeds specified limit conditions.

ENTRY. (See Life Phases)

ENVIRONMENTS.

NATURAL ENVIRONMENT: External conditions that exist in nature independent of the vehicle, such as temperature, pressure, radiation, winds, gusts, precipitation, meteoroids, and dust.

MAN-MADE ENVIRONMENT: External conditions made by man that exist independent of the vehicle, such as sonic booms, explosions, and air contaminants.

INDUCED ENVIRONMENT: Conditions created by the vehicle or its systems or by the response of the vehicle to the natural environment; for example, aerodynamic pressures and forces, aerodynamic heating, rocket-exhaust pressures and heating, wind-induced bending loads, and differential pressures during ascent.

FACTORS.

ULTIMATE FACTOR OF SAFETY: A multiplying factor applied to limit load (or pressure) to obtain ultimate load (or pressure). The factor of safety is used to account for design uncertainties that cannot be analyzed or accounted for in a rational manner. For example, a factor of safety would be used because of the designer's inability to predict residual stresses or because fabrication processes cannot be controlled to produce ideal or identical structure.

YIELD FACTOR OF SAFETY: The ratio of the load at which the structure undergoes detrimental deformation to the limit load.

ULTIMATE PRESSURE FACTOR OF SAFETY: A multiplying factor applied to limit pressure to obtain ultimate pressure.

YIELD PRESSURE FACTOR OF SAFETY: The ratio of the pressure at which a pressure vessel undergoes detrimental deformation to the limit pressure.

PROOF FACTOR: A multiplying factor applied to either limit load or limit pressure to obtain either proof load or proof pressure.

SPECIAL STRENGTH FACTORS: Factors which may be applied for special purposes other than those normally included in the ultimate or yield factors of safety.

FAIL-SAFE. A design philosophy under which failure propagation is so limited that the failure of any single structural component will not degrade the strength or stiffness of the remainder of the structure to the extent that the vehicle cannot complete the mission at a specified percentage of limit loads.

FAILURE. A rupture, collapse, or seizure, an excessive wear, or any other phenomenon resulting in an inability to sustain design loads, pressures, and environments without detrimental deformation.

FATIGUE. In materials and structures, the cumulative irreversible damage incurred by the cyclic application of loads and environments. Fatigue can cause cracking and cause degradation in the strength of materials and structures.

FLUTTER. A self-excited oscillation caused and maintained by the aerodynamic, inertia, and elastic forces in the structural system of the vehicle.

FRACTURE MECHANICS. An engineering concept used to predict the initiation and propagation of cracks leading to fracture of structures.

HORIZONTAL TAKEOFF. (See Life Phases)

INTERFACE. The common boundary between components, assemblies, or systems of a space vehicle. An interface may be physical, functional, or procedural.

LANDING. (See Life Phases)

LAUNCH. (See Life Phases)

LIFE PHASES. Subdivisions of vehicle flight which are characterized by a related set of design conditions. Two categories of life phases may be identified: (1) those related to flight operations, including prelaunch, launch, ascent, space, entry, atmospheric flight, and landing; and (2) those related to ground operations, including manufacturing, storage, refurbishment, transportation and ground handling, and horizontal takeoff. Phase definitions are as follows:

PRELAUNCH PHASE: The interval beginning with completion of vehicle installation on the launch pad and terminating with commencement of final countdown.

LAUNCH PHASE: The interval beginning at final countdown and terminating at the instant of vertical liftoff, holddown release, or engine shutdown for an on-pad abort.

ASCENT PHASE: The interval beginning at the instant of vertical liftoff or holddown release and terminating with the decay of thrust-cutoff transients at insertion into orbit for the orbiter or at separation for the booster.

SPACE PHASE: The interval beginning with the decay of thrust-cutoff transients at orbit insertion and terminating with initiation of deorbit retro impulse. The space phase includes orbit, rendezvous, docking, undocking, cargo transfer, and mechanical operations in space.

ENTRY PHASE: For the orbiter, the interval beginning with the initiation of deorbit retro impulse and terminating after the transition of the orbiter to aerodynamically controlled flight. For the booster, the interval beginning at the instant of separation from the orbiter and terminating after the transition of the booster to aerodynamically controlled flight.

ATMOSPHERIC FLIGHT PHASE: The interval beginning with the transition of the orbiter or booster to aerodynamically controlled flight or beginning when the orbiter or booster becomes airborne in horizontal takeoff and terminating the instant before touchdown.

LANDING PHASE: The interval beginning with touchdown of the orbiter or booster and terminating after the landing and taxi run. Landing includes touchdown, landing roll, braking, and taxiing.

MANUFACTURING PHASE: The interval beginning with the manufacture of vehicle hardware and terminating when the vehicle and/or its systems, assemblies, or components are accepted for shipment from the manufacturing facility to the launch site or storage area. Manufacturing includes receiving, inspection, fabrication, assembly, and checkout operations.

STORAGE PHASE: An interval during which a vehicle and/or its systems, assemblies, or components are stored in an inactive condition.

REFURBISHMENT PHASE: An interval during which a vehicle and/or its systems, assemblies, or components are repaired, replenished, inspected, or tested.

TRANSPORTATION AND GROUND HANDLING PHASE: Intervals and events during which the vehicle and/or its systems, assemblies, or components are handled, transported, or erected. Each transport interval begins when the vehicle is accepted or certified for shipment and terminates when the shipment is received at its destination. Ground handling includes such events as towing, hoisting, reorienting, carrying, erecting, jacking, and mooring.

HORIZONTAL TAKEOFF PHASE: The interval beginning with the taxiing of the orbiter or booster and terminating when the vehicle becomes airborne. Horizontal takeoff includes taxiing, braking, and takeoff roll.

LIMIT CYCLE. An oscillatory response of limited amplitude, usually due to a nonlinear parameter in a system.

LOADS.

LIMIT LOAD: The maximum load expected to act on a structure in the expected operating environments.

ULTIMATE LOAD: The product of the limit load and the ultimate factor of safety. It is the maximum load which the structure must withstand without rupture or collapse in the expected operating environments.

YIELD LOAD: The load below which no detrimental deformation will occur in the expected operating environments.

ALLOWABLE LOAD: The load that induces the allowable stress in a material.

APPLIED LOAD: A load imposed on the structure.

PROOF LOAD: The product of the limit load and the proof factor. It is the load applied to the structural components or assemblies as the basis for evaluating quality and workmanship prior to acceptance of the structure.

LOAD FACTOR. The ratio of the vector sum of the external forces acting on a mass to the weight of the mass.

LOAD REDISTRIBUTION. The changes in load distribution due to elastic deformation of the vehicle.

LOAD SPECTRUM. A representation of the cumulative static and dynamic loadings anticipated for a structural component or assembly under all expected operating environments.

LOAD TYPES.

STEADY LOAD: A load of constant magnitude and direction with respect to the structure. Examples are loads caused by joint preloads, clamping, and constant thrust.

QUASI-STEADY LOAD: A time-varying load in which the duration, direction, and magnitude are significant, but the rate of change in direction or magnitude and the dynamic response of the structure are not significant. Examples are loads caused by wind shear, thrust changes, lift, and drag.

IMPULSE LOAD: A suddenly applied pulse or step change in loading in which the duration, direction, magnitude, and rate of change in direction or magnitude are significant, and the dynamic response of the structure is also significant. Examples are loads produced by physical impact, vehicular pyrotechnics, and external explosions.

FLUCTUATING LOAD: An oscillating load in which the duration, direction, magnitude, frequency content, and phase are significant. Dynamic response of the structure may or may not be significant. Examples are loads caused by pogo-type instability, flutter, buffeting, aerodynamic noise, acoustic noise, and rotating equipment.

MALFUNCTION. A failure of any functional component, assembly, or system to operate in accordance with applicable procedures, drawings, and specifications.

MANUFACTURING. (See Life Phases)

MARGIN OF SAFETY. The increment by which the allowable load (i.e., ultimate or yield) exceeds the applied load for a specific design condition, expressed as a fraction of the applied load.

$$MS = \frac{A - D}{D} = \frac{1}{R} - 1$$

where

A = allowable ultimate or yield load

D = actual or applied load

R = ratio D/A

Thus, the strength or stiffness capability of the structural components or assemblies can be evaluated at various times to assess the relative strength or stiffness of these elements at all critical service conditions. The margins so determined are used as final indicators of available strength or adequate stiffness after all other design characteristics, conditions, and factors have been accounted for.

MISSION. A single flight endeavor undertaken by the vehicle.

PRELAUNCH. (See Life Phases)

PRESSURES.

DESIGN PRESSURES FOR PRESSURE VESSELS:

Limit Pressure. The maximum differential pressure that can be expected to occur in service under the expected operating environments. Limit pressures include maximum operating pressure, transient pressure, and head pressure.

Yield Pressure. The differential pressure below which no detrimental deformation will occur anywhere in a pressure vessel in the expected operating environments.

Ultimate Pressure. The maximum differential pressure which a pressure vessel must sustain without rupture in the expected operating environments. It is equal to the product of the limit pressure and the ultimate pressure factor.

DUE TO PRESSURIZATION EFFECTS ONLY:

Nominal Operating Pressure. The maximum pressure applied to a pressure vessel by the pressurizing system with the pressure regulators and relief valves at their nominal settings and with nominal fluid flow rate.

Maximum Operating Pressure. The maximum pressure applied to a pressure vessel by the pressurizing system with the pressure regulators and relief valves at their upper limit and with the maximum fluid flow rate.

Transient Pressure. Time-dependent pressure in which the characteristic time of fluctuation is comparable to significant dynamic time constants of the structure and vehicle systems; for example, the pressure fluctuation caused by the opening and closing of valves, pump surges, flutter of check or relief valves, engine's thrust transients, engine gimbaling, and fluid sloshing.

Head Pressure. Static head pressure is the pressure at any point below the liquid level in a pressure vessel due to the height of the column of liquid in a gravity field. Dynamic head pressure is the additional pressure caused by acceleration.

TEST PRESSURES:

Proof Pressure. The pressure that pressurized components must sustain to give evidence of satisfactory workmanship and material quality, and to establish the maximum undetected flaw size. It is equal to the product of limit pressure and proof factor.

Burst Pressure. The pressure at which a pressurized component ruptures.

PRESSURE VESSEL. A container designed primarily to sustain internal pressure, but which may also carry some vehicle loads.

PRESSURIZED STRUCTURE. A structure designed primarily to carry vehicle loads, but which may also be subjected to internal pressure (e.g., cabins, interstages, heat shields, insulation panels, and honeycomb structure).

PROBABILISTIC. Denotes that the values used in design are random, not discrete. Probabilistic values are chosen on the basis of statistical inference. (See Deterministic)

SAFE-LIFE. A design philosophy under which failure or abort will not occur because of undetected flaws or damage during the specified service life of the vehicle; also, the period of time for which the integrity of the structure can be ensured in the expected operating environments.

SERVICE LIFE. The interval beginning with manufacture of a vehicle and ending with completion of its specified missions.

SPACE. (See Life Phases)

SPEEDS. (The following definitions apply to the booster and orbiter while either vehicle is operating within the dynamic-pressure load-factor-temperature envelope and is relying on forces other than thrust to sustain lift.) Speed is expressed in terms of equivalent airspeed (EAS).

DESIGN SINK SPEED: The maximum vertical descent speed at touchdown in the landing configuration.

LEVEL FLIGHT MAXIMUM SPEED, V_H: For the basic configuration, the maximum speed attainable in level flight at any altitude with maximum thrust.

LIMIT SPEED, V_L: For the basic- and high-drag configurations, the maximum speed attainable commensurate with the operational use of the vehicle.

LIMIT SPEED, V_{LF}: For the landing approach and takeoff configurations, a value of 120 percent of (1) the maximum speed attainable without exceeding 200-ft altitude after takeoff from a runway or from an aborted landing over the period of time required to convert from the takeoff condition to the basic flight configuration, or (2) 1.75 times the stalling speed, V_S, whichever is higher.

STALLING SPEED, V_S: For the basic flight configuration, the minimum speed for stable flight at sea level with zero thrust.

STALLING SPEED, V_{SL}: For the basic landing-approach configuration, the minimum speed for stable flight at sea level with zero thrust.

STALLING SPEED, V_{SPA}: For the basic landing configuration, the minimum speed for stable flight at sea level with the power or thrust required to provide satisfactory go-around characteristics.

SPEED FOR MAXIMUM GUST, V_G: For the basic configuration, the speed determined either by the intersection of the line representing C_N maximum and the 66-fps gust line on the V-n diagram (fig. 5-5) or $V_{S1} \sqrt{n_g}$ where n_g is the gust load factor at V_H in accordance with the criteria presented in Section 5.2.10.1.2.1 and V_{S1} is the stalling speed of the basic configuration at the particular weight and altitude under consideration.

STIFFNESS. Structural resistance to deflection under an applied force or torque.

STORAGE PHASE. (See Life Phases)

STRENGTH.

MATERIAL STRENGTH: The stress level that the material is capable of withstanding in the local structural configuration in the expected operating environments. Units are expressed in pounds per unit area (original unloaded cross-sectional area).

YIELD STRENGTH: Corresponds to the maximum load or stress that a structure or material can withstand without incurring detrimental deformation.

ULTIMATE STRENGTH: Corresponds to the maximum load or stress that a structure or material can withstand without incurring rupture or collapse.

STRESSES.

ALLOWABLE STRESS: The maximum stress that can be permitted in a material for a given design condition to prevent rupture, collapse, or detrimental deformation.

APPLIED STRESS: The structural stress induced by the applied load and environment.

RESIDUAL STRESS: A stress that remains in the structure due to processing or fabrication.

THERMAL STRESS: The structural stress arising from temperature gradients and differential thermal expansion between structural components, assemblies, or systems.

STRUCTURAL ADEQUACY OR INTEGRITY. A structure that complies with specified design requirements.

STRUCTURAL DESIGN TEMPERATURES. Temperatures of the structure when it is subjected to critical combinations of loads, pressures, and temperatures.

STRUCTURE. All components and assemblies designed to sustain loads or pressures, provide stiffness and stability, or provide support or containment.

SYSTEM. A major combination of components and assemblies that functions as a unit. (See Assembly and Component)

TRAJECTORY. The flight path of the space vehicle.

NOMINAL TRAJECTORY: The ideal trajectory the vehicle would follow as a point mass if external and internal characteristics and conditions were exactly as programmed.

DISPERSED TRAJECTORIES: Vehicle trajectories which vary from the nominal trajectory because of variations in tolerances of internal and external characteristics and conditions.

TRANSPORTATION AND GROUND HANDLING PHASE. (See Life Phases)

UNIPOTENTIAL STRUCTURE. A structure in which all components are electrically continuous with very low impedance between the structural components.

VEHICLE. The booster, orbiter, or both in mated configuration.

VIBRATION MODE. A characteristic pattern of displacement assumed by a vibrating system in which the motion of every particle is simple harmonic with the same frequency. Also referred to as Elastic Mode.

2. RELATED DOCUMENTS

NASA SPACE VEHICLE DESIGN CRITERIA SPECIAL PUBLICATIONS

SP-8001 Buffeting During Atmospheric Ascent. May 1964, Rev. Nov. 1970.

SP-8002 Flight-Loads Measurements During Launch and Exit. Dec. 1964.

SP-8003 Flutter, Buzz, and Divergence. July 1964.

SP-8004 Panel Flutter. July 1964.

SP-8005 Solar Electromagnetic Radiation. June 1965.

SP-8006 Local Steady Aerodynamic Loads During Launch and Exit. May 1965.

SP-8007 Buckling of Thin-Walled Circular Cylinders. Sept. 1965, Rev. Aug. 1968.

SP-8008 Prelaunch Ground Wind Loads. Nov. 1965.

SP-8009 Propellant Slosh Loads. Aug. 1968.

SP-8012 Natural Vibration Modal Analysis. Sept. 1968.

SP-8013 Models of the Meteoroid Environment–1969 (Near Earth to Lunar Surface). Mar. 1969.

SP-8014 Entry Thermal Protection. Aug. 1968.

SP-8016 Effects of Structural Flexibility on Spacecraft Control Systems. Apr. 1969.

SP-8018 Spacecraft Magnetic Torques. Mar. 1969.

SP-8019 Buckling of Thin-Walled Truncated Cones. Sept. 1968.

SP-8021 Models of Earth's Atmosphere (120 to 1000 km). May 1969.

SP-8022 Staging Loads. Feb. 1969.

SP-8024 Spacecraft Gravitational Torques. May 1969.

SP-8029 Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent. May 1969.

SP-8030 Transient Loads from Thrust Excitation. Feb. 1969.

SP-8031 Slosh Suppression. May 1969.

SP-8032 Buckling of Thin-Walled Doubly Curved Shells. Aug. 1969.

SP-8033 Spacecraft Earth Horizon Sensors. Dec. 1969.

SP-8034 Spacecraft Mass Expulsion Torques. Dec. 1969.

SP-8035 Wind Loads During Ascent. June 1970.

SP-8036 Effects of Structural Flexibility on Launch Vehicle Control Systems. Feb. 1970.

SP-8040 Fracture Control of Metallic Pressure Vessels. May 1970.

SP-8042 Protection Against Meteoroids. May 1970.

SP-8043 Design Development Testing. May 1970.

SP-8044 Qualification Testing. May 1970.

SP-8045 Acceptance Testing. Apr. 1970.

SP-8046 Landing Impact Attenuation for Non-Surface-Planing Landers. Apr. 1970.

(The following NASA Space Vehicle Design Criteria Special Publications, not yet published, are available in draft form from the Space Vehicle Design Criteria Office at the NASA-Langley Research Center.)

SP-80XX Compartment Venting

SP-80XX Entry Gasdynamic Heating

SP-80XX Deployable Aerodynamic Deceleration Systems

SP-80XX Structural Vibration Prediction

SP-80XX Prevention of Coupled Structure-Propulsion Instability (Pogo)

SP-80XX Space Radiation Protection

SP-80XX Protection Against Explosive Shock

SP-80XX Stress-Corrosion Cracking

SP-80XX Nuclear and Space Radiation Effects on Materials

SP-80XX Mechanical Shock Response Analysis

SP-80XX Transportation and Handling Loads

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MIL-A-8861(ASG) Airplane Strength and Rigidity – Flight Loads. May 18, 1960.*

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MIL-A-8865(ASG) Airplane Strength and Rigidity – Miscellaneous Loads. May 18, 1960.*

MIL-A-8866(ASG) Airplane Strength and Rigidity – Reliability Requirements, Repeated Loads, and Fatigue. May 18, 1960.**

MIL-A-8867(ASG) Airplane Strength and Rigidity – Ground Tests. May 18, 1960.**

MIL-A-8868(ASG) Airplane Strength and Rigidity – Data and Reports. May 18, 1960.**

MIL-A-8870(ASG) Airplane Strength and Rigidity – Vibration, Flutter and Divergence. May 18, 1960.*

MIL-A-8871(USAF) Airplane Strength and Rigidity – Flight and Ground Operations Tests. Oct. 8, 1968.*

MIL-A-8892(USAF) Airplane Strength and Rigidity – Vibration. To be published April 1971.*

MIL-A-8893(USAF) Airplane Strength and Rigidity – Sonic Fatigue. To be published April 1971.*

MIL-B-5087B(ASG) Bonding, Electrical, and Lightning Protection for Aerospace Systems. Oct. 15, 1964.

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MIL-HDBK-17 Plastics for Flight Vehicles. Aug. 14, 1961.

MIL-HDBK-23A Structural Sandwich Composites. Dec. 30, 1968.

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MIL-STD-785A Reliability Program for Systems and Equipment, Development and Production. Mar. 28, 1969.

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**Document expected to be revised by June 1971.

3. DESIGN OBJECTIVES

Structural design is strongly affected by objectives which cannot be absolutely defined or imposed because of performance, risk, cost, or other factors that depend on the hazards involved, the mission constraints, or details of the vehicle, its structure, and mode of operation. The following paragraphs present objectives to be pursued in space-shuttle structural design.

3.1 WEIGHT

Because of the significant influence of structural weight on vehicle performance, the design of structure other than pressure vessels should be based only upon critical flight, landing, and takeoff conditions, including the cumulative effect of repeated service environments.

So far as practicable, designs should be selected so that the burden of accommodating nonflight loads is borne by ground equipment, rather than by flight equipment and structure.

Vehicle loads associated with ferry conditions should not exceed design levels for other flight phases.

3.2 MANUFACTURABILITY

The structural design should employ proven processes and procedures for manufacture and repair. Provision should be made for inspection during manufacture.

3.3 SIMPLICITY

The structural design should emphasize simplicity in the form and combination of components, assemblies, and systems to facilitate accurate determination of load paths and to increase confidence in the calculated stresses, strains, and structural response.

3.4 MAINTAINABILITY

The structural design should permit the vehicle structure to be maintained in or restored to a flightworthy condition with a minimum of resources. The design should emphasize structural materials, forms, fasteners, and seals which minimize the need for maintenance and which properly consider the needs for access, inspection, service, replacement, repair, and refurbishment.

3.5 ACCESSIBILITY

Structural design should permit adequate access to components and to structure for inspection or refurbishment for reuse. The structure should be designed so that no specific order of removal and reinstallation of access doors and panels is imposed only for structural considerations. Components having a high probability of replacement should be located so they can be readily replaced.

3.6 INTERCHANGEABILITY

The structural capability should not be degraded when replacement components, assemblies, or systems are installed.

3.7 REPAIR

The structural capability should not be degraded by repair nor should the design include allowances for possible degradation from repair. Repaired structure should meet all stipulated conditions of flightworthiness.

3.8 TANK SERVICEABILITY

The structural design should permit filling and emptying tanks in any order while the vehicle is on the launcher. Provision should be made to prevent the absolute internal pressure from decreasing to a value less than the external ambient pressure when tanks are being emptied.

3.9 COST

The structure should be designed to minimize the total cost of the space shuttle for 100 missions, including costs of development, production, and any servicing, inspection, repair, or refurbishment necessary to carry out the missions.

3.10 COMPATIBILITY OF REQUIREMENTS

To facilitate the development of compatible structure, the following requirements or constraints should be established as early as possible in the design process:

- Safety
- Reusability
- Life
- Load factors
- Turnaround time
- Risk/reliability
- Mission duration
- Mission abort
- Allowable leakage rates.

4. DESIGN CHARACTERISTICS

The vehicle structure shall possess adequate strength and stiffness to withstand limit loads and pressures in the expected operating environments throughout its service life without experiencing detrimental deformation, as defined in Section 1.6. The structure shall withstand ultimate loads and pressures in the expected operating environments without experiencing rupture or collapse. All pressure vessels in the vehicle shall sustain proof pressure without incurring detrimental deformation. When proof tests are to be conducted at temperatures other than flight temperatures, the degradation of material properties at flight temperatures shall be accounted for in determining the proof pressure.

The correction factor is equal to the ratio of estimated burst pressure at proof temperature to the burst pressure at critical design temperature.

Pressure vessels shall be capable of withstanding ultimate pressure and ultimate load without experiencing rupture or collapse under destabilizing pressure. When pressure is stabilizing, pressure vessels shall be capable of withstanding limit pressure and ultimate load without experiencing rupture or collapse. The most probable failure mode for pressure vessels shall be leakage, rather than rupture.

If the protection against environments afforded by the overall vehicle design is not sufficient to limit detrimental effects to specified levels, provision shall be made for protection against these environments.

The structure shall not be designed to withstand loads, pressures, or environments due to malfunctions that would in themselves result in failure to accomplish the mission.

Pertinent mass, physical, mechanical, thermal, and dimensional properties of the vehicle shall be identified and accounted for under all the design conditions the vehicle is expected to encounter in all phases of its service life.

4.1 LOADS AND PRESSURES

4.1.1 LIMIT-LOAD DETERMINATION

Limit loads shall be determined for the vehicles, in either mated or unmated configurations, for the design conditions identified in Section 5. These loads shall be consistent with the design objectives stated in Section 3, and with the criteria for limit pressures (Sec. 4.1.2), thermal characteristics (Sec. 4.6), and material characteristics (Sec. 4.7).

At least the following effects and their perturbations, dispersions, and time histories shall be accounted for, as appropriate: (1) the vehicle's external and internal geometry; (2) mass distribution, stiffness, and damping of the vehicle, including changes in properties due to load level and thermal environment, and load redistribution resulting from elastic deformation; (3) aerodynamic characteristics; (4) natural, man-made, and induced environments; (5) the interactions of propulsion, control, and other vehicle systems; and (6) trajectory characteristics. The limit loads shall be based on consistent combinations of these parameters, accounting for operational procedures and sequences and commanded values of controllable variables such as engine-ignition sequence, launch release, navigation, attitude control, staging, and docking.

Limit loads are derived by combining external and internal loads at potentially critical flight conditions. Traditionally, several cycles of load prediction and assessment are required. Starting with idealized structure, the "limit load" is based initially on steady and quasi-steady *externally* applied loads obtained from preliminary information on rigid-body aerodynamics, vehicle contours, flight profiles, and weights. The *internal* and dynamic load contributions to limit load are then determined from more detailed knowledge of substructure, load paths, and elastic response. Redistribution of loads and resizing or refinement of structure then proceed either to a final design if mission and program requirements are met or, if confidence in the results is lacking, to another cycle of load prediction and assessment.

At present, there are no standards for ensuring conservatism without causing an impact on other mission requirements. The treatment of uncertainties that arise because of load excursions, lack of input data, or concern over the method of load analysis is based on judgments which, applied to substructure individually, may be conservative but, applied collectively to the total structure, may not. For example, load uncertainties are sometimes combined

TABLE 4-1 **ILLUSTRATIVE LIMIT-LOAD PROBABILITIES**

MISSION PHASE	DEFINITION OF PROBABILITY VALUE	LIMIT-LOAD PROBABILITY LEVEL (95% CONFIDENCE)
Prelaunch	Probability of <u>not</u> having to return a vehicle from the pad to the assembly area, or to implement special tie-down procedures because of structural capability limitations with respect to the prelaunch ground environment.	99%
Launch	Probability of <u>not</u> having to delay a launch because of structural capability limitations with respect to the launch ground environment.	99%
Ascent	Probability of <u>not</u> having to delay a launch because of structural capability limitations with respect to the anticipated ascent environment.	95%
Separation	Probability of <u>not</u> having to abort a mission because of structural capability limitations with respect to the separation environment.	99.9%
Space	Probability of <u>not</u> having abnormal space operations because of structural capability limitations with respect to the associated environments.	99%
Entry	Probability of <u>not</u> having to alter the entry flight plan because of structural capability limitations associated with the anticipated entry environment.	99%
Atmospheric flight	Probability of <u>not</u> having to delay entry or <u>not</u> having to select an alternate landing site because of structural capability limitations with respect to anticipated atmospheric environments.	99%

with other uncertainties (hazard, fabrication, material properties, etc.) and included in the factor of safety; this practice can lead to unconservatism or inconsistency in design if the same factor is used by all contractors. Because visibility is necessary, the recommended approach is to document, segregate, and account quantitatively for all uncertainties that may influence a design decision.

Considerable emphasis is being placed on automated methods and finite-element computer programs such as NASTRAN to speed up and improve the load-determination process. In particular, there is need for a rational approach for defining and treating uncertainties, other than by use of arbitrary factors or arbitrary methods of load combination (e.g., peak on peak). Attempts to achieve such an approach include refinement of the probabilistic values to characterize better the environments and to define the limit load statistically in terms of its probability of occurrence at a specified confidence level. This approach requires extensive test data on all load-input parameters to describe the loads properly; a requirement that presently limits its use during preliminary design. However, probabilistic methods are well suited for providing an insight to the sensitivity of the structure to loads, environments, and other variables, for establishing reliability goals, and for design evaluation *after* experimental data become available. In application, an overall nonexceedance probability level may be specified as illustrated in table 4-1, and individual load levels deduced so that this value is not exceeded.

The present state of quantitative knowledge of load conditions for shuttle-type vehicles leads to a structure for which the uncertainties can be assessed only with a low level of confidence. Where probability values are stated in this document, the reference is to the individual load contributions rather than to the overall failure probability of the structure. In these cases, the individual loads are to be combined statistically to obtain the limit load.

4.1.2 LIMIT-PRESSURE DETERMINATION

The design-limit values for, regulated pressure (e.g., in propellant tanks or personnel and cargo compartments) shall be based on the upper limit of the relief-valve setting when pressure is detrimental to structural load-carrying capability. When pressure increases the structural load-carrying capability (as in buckling), the lower limit of the operating pressure shall be used in determining the critical limit-pressure value.

Nonregulated pressures (e.g., in vented compartments or rocket-motor cases) shall be determined and accounted for in a rational manner. Where a range of pressure is possible for a particular design point, an upper and a lower bound of pressure shall be established for use in design. When pressure decreases the structural load-carrying capability, the maximum pressure shall be the limit-pressure value. When pressure increases the structural load-carrying capability, the minimum pressure shall be accounted for in determining the critical limit-pressure value.

4.2 DESIGN FACTORS

Any design factors used shall be identified, including factors of safety, special factors, and uncertainty factors. Considerations involved in establishing the values of all design factors shall be defined.

Factors of Safety. Currently, many design factors, including hazard factors, material-uncertainty factors, and load-uncertainty factors, are lumped into a single factor of safety. To avoid this lumping of factor on factor, it is recommended that the factor of safety be reserved for the accountability of only those uncertainties in the *load-carrying capability* of the structure which cannot be analyzed or otherwise accounted for in a rational manner. These uncertainties often arise from the inability to predict residual stresses or when fabrication processes are not ideal and cannot be controlled to produce ideal or identical structures. In addition, it is recommended that factors of safety be applied only to mechanically induced limit loads and pressures and not to temperatures or temperature gradients.

The selection of factor-of-safety values is presently arbitrary and the rationale varies with NASA center, project, and contractor. The values given in table 4-2 are recommended values to be applied to limit loads or pressures as starting points for the design of the shuttle vehicles. It is intended that these factors be verified or modified on the basis of the best available design techniques (e.g., fracture mechanics and statistical analyses as sufficient data become available) and that the values be consistent with the desired level of structural reliability.

TABLE 4-2 **FACTORS OF SAFETY**

COMPONENT*	FACTORS		
	Yield	Ultimate	Proof
General unpressurized structure	$\geq$1.0	1.5	–
Windows, doors, and hatches	–	3.0	2.0
Pressurized structure**	$\geq$1.0 –	1.5 2.0	– 1.5
Pressurized lines and fittings	–	2.5	1.5
Main propellant tank	1.1	1.4	1.05
Pressure vessels (other than propellant tanks)	–	2.0	1.5

*See paragraph 1.6 for definition of terms

**For pressurized structure, both ultimate factors of safety indicated should be applied as follows:

1.5 x limit load +1.0 x limit pressure (i.e., 1.5 x limit load applied at limit pressure)

and

0 x limit load +2.0 x limit pressure (i.e., 2.0 x limit pressure applied at zero limit load)

Special Factors. It is recommended that the following factors, as well as others relating to personnel safety and to strength, compatibility of materials, or type of construction be defined separately from factors of safety and applied in design, where appropriate:

Factor	Basis for Application
Hazard	Accounts for personnel safety when structure contains pressure or other stored energy
Stress concentration	Accounts for high local stress concentrations (e.g., at holes, corners, or fillets)
Fitting	Accounts for unknown stresses in complex joints or fittings
Material	Accounts for material-property scatter, flaws, brittle or fragile materials, and variations in process control
Casting	Accounts for process-control variations such as sensitivity to cooling rate and size
Weld	Accounts for variations in process control, rewelds, etc.
Buckling	Accounts for unknown strains introduced by end conditions, construction, cutouts, etc.

4.3 MARGIN OF SAFETY

The margin of safety shall be positive and shall be determined at allowable ultimate levels and yield levels, when appropriate, at the temperatures expected for all critical conditions.

For minimum-weight design, the margin of safety should be as small as practicable.

4.4 STATIC ELASTICITY

The vehicle structure shall be stiff enough so that static elastic deformation will not cause structural failure or degrade stability and control below specified levels.

4.4.1 DIVERGENCE

The vehicle shall be free from divergence at dynamic pressures up to: (1) 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories; (2) the maximum dynamic pressure expected along the dispersed abort trajectories; or (3) 1.32 times the maximum dynamic pressure expected at any point during atmospheric flight, with or without control surfaces activated. At (3), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

The evaluation should include, as appropriate, such factors as static and transient thermal effects on distortion and stiffness, loading magnitudes and distributions for all critical conditions, control-surface actuator-system stiffness characteristics, system tolerances, misalignments, and free play. For recommended practices, refer to NASA SP-8003.

4.4.2 CONTROL-SURFACE REVERSAL

For any given flight regime, the active aerodynamic control surfaces shall not exhibit reversal up to 1.32 times the maximum dynamic pressure expected at any Mach number within the dispersed flight envelope. The dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

For recommended practices, refer to NACA TN-3030.

Evaluation of the structure and the flight control system shall account for the aeroelastically modified control effectiveness under all relevant conditions.

During aborted flight, sufficient control effectiveness should be retained to permit the safe return of the vehicle and personnel.

4.4.3 BUCKLING AND CRIPPLING

Buckling shall not cause components that are subject to instability to collapse when ultimate loads are applied, nor shall buckling deformation from limit loads degrade the functioning of any system or produce changes in loading that are not accounted for.

Evaluation of buckling strength shall consider (1) general instability, (2) local or panel instability, (3) crippling resulting from combined action of primary and secondary stresses, and (4) creep.

All structural components that are subject to compressive inplane stresses under any combination of ground or

flight loads, including loads resulting from temperature changes, shall be investigated for buckling failure. Design loads for buckling shall be ultimate loads, except that any load component that tends to alleviate buckling shall not be increased by the ultimate factor of safety. External-pressure or torsional (destabilizing) limit loads shall be increased by the ultimate factor of safety, but internal-pressure (stabilizing) loads shall not be increased unless they reduce structural capability.

For recommended practices, refer to NASA SP-8007, SP-8019, and SP-8032.

4.5 DYNAMIC ELASTICITY

The structure shall be designed to: (1) prevent all detrimental instabilities of coupled vibration modes; (2) minimize detrimental effects of the loads and dynamic responses which are associated with structural flexibility; and (3) minimize adverse interaction between the structure and other vehicle systems. Analyses shall account for:

1. **Configuration effects, such as center-of-gravity offset leading to coupled response.**
2. **Unsymmetrical stiffness distribution.**
3. **Variations in characteristics of the vehicle-pad release-restraint device.**
4. **Thrust-load variations and unsymmetrical thrust effects resulting from engine sequencing and non-uniformity in combustion (including engine-out conditions).**
5. **Unsymmetrical aerodynamic effects.**

The fulfillment of the strength requirements should not be deemed sufficient in itself to satisfy dynamic and elasticity requirements. The following items should be evaluated: (1) changes in stiffness due to structural temperatures and internal stress redistribution with increasing load level; and (2) effects of clearances and free play.

4.5.1 DYNAMIC AEROELASTIC INSTABILITIES

4.5.1.1 CLASSICAL FLUTTER

The vehicle shall be free from flutter at dynamic pressures up to: (1) 1.32 times the maximum dynamic pressure expected at any point along the dispersed ascent and entry design trajectories; (2) the maximum dynamic pressure expected at any point along the dispersed abort trajectory; or (3) 1.32 times the maximum dynamic pressure expected at any point during atmospheric flight, with or without control surfaces activated. At (3), the dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

The evaluation should account for all pertinent aerodynamic, elastic, inertia, and damping parameters, and coupling mechanisms (e.g., mechanical, elastic, and aerodynamic), as well as the effects of control-system characteristics and free play, misalignments, booster-orbiter interface stiffness, and cryogenic tank-support structural freedoms. If staging can occur in the atmosphere, the changes in vibration-mode characteristics and in the characteristics of the newly activated control surfaces should be accounted for, as well as the location of the lifting or control surfaces on the separating space-shuttle vehicles. For recommended practices, refer to NASA SP-8003.

4.5.1.2 STALL FLUTTER

Separated aerodynamic-flow effects associated with lifting and stabilizing surfaces in high angle-of-attack maneuvers shall not result in structural failure. The vehicle shall be free of stall flutter at 1.32 times the dynamic pressure expected for this type of maneuver.

A parametric evaluation of vehicle stall-flutter characteristics should be conducted to determine the necessary aeroelastic characteristics to avoid limit-cycle amplitude responses that could induce adverse loads on the structure. The evaluation should consider:

1. Separated-flow characteristics under all anticipated conditions of angle of attack and speed.
2. Stiffness, inertia, and damping characteristics of the aerodynamic surfaces.
3. All significant degrees of freedom.

4.5.1.3 PANEL FLUTTER

External surfaces shall be free of panel flutter at all dynamic pressures up to: (1) 1.5 times the local dynamic pressure expected to be encountered at any Mach number in flight; and (2) the maximum dynamic pressure expected for dispersed abort trajectories. The dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

The structural design of panel configurations for flutter prevention should be based upon consideration of the following parameters: panel stiffness, edge constraints,

panel-support-structure stiffness, midplane stresses, thermal environment, local dynamic pressure and Mach number, differential pressure (including the effects of venting), and direction of flow.

Panel flutter should be prevented in all modes, including first-vibration-mode flutter, and in traveling-wave and standing-wave phenomena. For recommended practices, refer to NASA SP-8004.

4.5.1.4 CONTROL-SURFACE BUZZ

The vehicle shall be free of control-surface buzz at dynamic pressures up to 1.32 times the maximum dynamic pressure expected to be encountered in flight, with or without control systems activated. The dynamic-pressure margin shall be determined separately at constant density and at constant Mach number.

Control surfaces shall not exhibit sufficient buzz to cause structural failure, loss of control of the vehicle, or otherwise impair the safe return of personnel at the maximum dynamic pressure or at any Mach number along dispersed abort trajectories.

Provision should be made in initial design for sufficient space, rigidity, and strength to incorporate dampers, in anticipation of their possible use.

The following considerations should be reflected in the design:

1. Aerodynamic configurations should be carefully selected so that flow-separation positions minimize the onset of buzz.
2. High torsional and rotational rigidity should be provided to ensure the highest practical rotational frequency.
3. The design should incorporate close-tolerance bearings, actuator linkage, and attachments to minimize free play.

For recommended practices, refer to NASA SP-8003.

4.5.2 DYNAMIC COUPLING

4.5.2.1 FLIGHT-CONTROL SYSTEM AND ELASTIC MODES

The vehicle shall be free of instability or other interactions of the control system and the elastic modes which could impair flightworthiness. Structural characteristics shall be defined in sufficient detail to permit the prediction of interactions of the control system and elastic modes by means of analysis. Freedom from undesirable interactions shall be demonstrated by analysis, supplemented by tests. The analysis shall account for the effect of engine thrust and assume worst-case values for structural damping and stiffness at critical times during flight.

The influence of selected control systems and concepts upon loads and dynamic response should be evaluated. Detrimental effects should be prevented by specification of appropriate control-system parameters such as stability and phase margins when this can be accomplished without degradation of performance. Load-alleviation control systems should be evaluated in the context of overall system performance, including evaluation of parameter sensitivity. The evaluation should consider the effects of: (1) excitation of the structure and control system by induced and natural environments; (2) changes in configuration and parameters of the vehicle and control system; (3) elastic modes (reflecting mated vehicle coupling, where appropriate); (4) nonlinear and time-variant factors; (5) pilot-in-the-loop; and (6) actual hardware.

Special consideration should be given to the design of the following components from the standpoint of minimizing detrimental interaction with the guidance and control system: (1) actuators, (2) sensor mounts, (3) joints, (4) engine-support structure, (5) structural components integral to the passive control systems, (6) control and retrorocket mounts, (7) rotating machinery, (8) control surfaces, and (9) appendages. The interface structure integrating the guidance and control system and the vehicle structure should be designed so that the excitations transmitted from the vehicle do not impair the performance of the guidance and control system or produce unacceptable error drift. For recommended practices, refer to NASA SP-8016 and SP-8036.

4.5.2.2 SLOSH

Tanks shall be designed to prevent or suppress coupling between liquids and vehicle structure, and between liquids and the flight-control system.

The need for slosh-suppression devices should be determined on the basis of dynamic analyses which consider the impact of slosh damping on vehicle overall loads, propellant tank local loads, control-system effectiveness, and overall vehicle stability. If found to be necessary, the slosh-suppression devices should be designed to provide the specified levels of slosh damping, to function

compatibly with all other systems in the vehicle, and to maintain their structural integrity under all applied loads.

The following characteristics shall be accounted for in slosh-suppression-device design:

1. **Tank characteristics, including size, geometry, internal hardware and structure, structural stability, internal insulation, and venting provisions.**
2. **Liquid-system characteristics, including liquid boiling, bubble entrapment, draining and settling, fluid level, fluid-material compatibility, and slosh frequencies.**
3. **Environmental conditions, including tank motions, temperature and pressure variations, thermal shock, and repeated loads.**
4. **Control-system parameters, such as frequencies and sensor-gain settings, characteristics, and locations.**

The design should be versatile enough to permit reconfiguration as a consequence of revised flight mission and inspection and refurbishment plans.

The design of slosh-suppression devices should utilize experimental flight data or full- or reduced-scale test data from appropriate configurations which incorporate the degree of damping provided by candidate devices. For recommended practices, refer to NASA SP-8009, SP-8031, and SP-8036.

4.5.2.3 STRUCTURE AND PROPULSION SYSTEM (POGO)

The design shall not permit unstable coupling of the structure with the liquid-propulsion system for all mission configurations.

Coupling of the structure with the liquid-propulsion system shall be evaluated with the use of a mathematical model that incorporates physical characteristics determined by experiment, where possible, and accounts for the following:

1. **Elastic-mode coupling of the vehicle structure, propellant feedlines, and tank-fluid system.**
2. **Engine characteristics, including engine-mounting flexibility, turbopump transfer functions, cavitation characteristics, and propellant-flow rates.**
3. **Delivery-system characteristics, including flexible supports, accumulators, pressure-volume compensators, fluid or gas injection, fluid damping, and flow resistances.**

It is recommended that the damping-gain margin be at least 6 dB and that the structural-phase margin be at least 30 degrees. For recommended practices refer to the forthcoming NASA special publication on prevention of coupled structure-propulsion instability (pogo) and NASA SP-8036.

4.5.3 DYNAMICALLY INDUCED ENVIRONMENTS

4.5.3.1 NOISE, VIBRATION, AND SHOCK

The structural response to acoustic and aerodynamic noise, vibration, and shock shall not cause structural failure or system or component malfunction, nor degrade performance below specified limits, nor shall it reduce vehicle service life or impair the safety or performance of personnel.

Stiffness and transmissibility characteristics of local structure and equipment-mounting hardware (e.g., brackets, panels, or trusses) should limit the applied shock and vibration environments to those compatible with component or system specifications.

The local resonances of the equipment mounts should be separated from the vehicle resonances and from the resonances of the structure and nearby equipment. Equipment-mounting hardware should be preloaded at installation to prevent gaps between mounting flanges and mounting structure during exposure to limit dynamic environments.

For recommended practices, refer to NASA SP-8012 and to forthcoming NASA special publications on structural vibration prediction, protection against explosive shock, and mechanical shock response analysis.

4.5.3.2 BUFFETING

The design of the vehicle shall minimize the detrimental effects of buffeting on the bodies and the aerodynamic surfaces at any point, including high angle-of-attack and transonic Mach-number environments. Buffeting phenomena shall not impair vehicle control or structural integrity, nor shall they impose a hazard to or accelerations on the personnel or cargo in excess of specified values.

For recommended practices, refer to NASA SP-8001.

4.6 THERMAL CHARACTERISTICS

The structure shall withstand without failure the effects of thermal-energy transfer due to the natural, man-made,

and induced thermal environments on the surface thermal-radiation properties, the structural material properties, and the thermal protection system (including insulation material).

The thermal protection system for heat sources or sinks shall maintain the vehicle structure and components at temperatures within the design constraints for all ground operation and flight conditions. Thermal protection system performance (e.g., the system unit weight required to limit a given structure to a given temperature) and the temperatures and temperature gradients of the system and structure shall be predicted from transient analyses that include thermal-energy sources and sinks. The thermal protection system and structure shall be analyzed as a complete system. The thermal protection and structural systems shall be compatible with each other and with other components with respect to temperature, deflections, and loads.

The analysis and design of thermal protection systems shall account for:

1. Characteristics that vary with time and temperature (e.g., oxidation, embrittlement, annealing, and creep).
2. Interdependent effects (e.g., stress-accelerated oxidation).
3. Conventional temperature-dependent characteristics (e.g., allowable strength, crippling allowables, and fatigue allowables).
4. Dimensional stability of contours, where appropriate, especially contours of leading edges, nose regions, and control surfaces.
5. Sealing requirements.
6. Manufacturability, refurbishment, and reuse requirements.
7. The effect of local or distributed roughness. External discontinuities shall be small compared with the boundary-layer displacement thickness. Steps shall be aft-facing with respect to local flow at critical heating. Beads, waves, and other local deviations from smooth contour shall be aligned parallel to the local flow at critical heating.

Stiffening and expansion-accommodating features in skin design shall be investigated by means of analysis and convective-heating tests.

Nonablative Heat Shields. Practical procedures shall be developed to detect damage from temperature or from variations in temperature with time.

Ablative Heat Shields shall resist degradation in the storage, ground handling, launch, and space environments, as well as provide adequate thermal protection during ascent and entry or abort. Shields to be used for more than one mission shall be designed with provision for nondestructive inspection to determine adequacy for reuse, considering such parameters as unpyrolized thickness, remaining char layer, and outgassing and related effects.

Cryogenic Thermal Protection Systems, including any purge-gas system, shall be designed to prevent or suitably limit atmospheric gases (including water vapor) not sealed in the system from condensing or freezing within the vehicle.

Insulation. System failures such as cracking, debonding, or sealant failures (caused by conditions such as thermal cycling, noise, vibration, or moisture absorption) that could result in structural failure shall be identified and evaluated. The extent, mode, and distribution of insulation failures identified analytically shall be verified by repeated testing of the insulation system under conditions simulating those expected during the service life of the insulation.

Protective Finishes and Surface Treatments. When protective finishes or surface treatments are used, the design shall account for degradation of the substrate or surrounding structure which might be caused by condensation, impingement, or sublimation from the coating, or by diffusion of coating or substrate elements.

The toxicity of outgassing products from heated coating materials shall be accounted for.

4.7 MATERIAL CHARACTERISTICS

Materials shall be characterized in sufficient detail to permit reliable and high-confidence predictions of material properties.

Materials shall have an adequate resistance to fracture and detrimental deformation when exposed to the anticipated loads, environments, and temperatures, and their variations with time.

Material characterization shall include determination of: (1) general physical properties, including thermal characteristics; (2) allowable mechanical properties; and (3) material failure mechanisms.

A unified program for material processing and quality control (e.g., for both structure and thermal protection system) should be followed throughout the design, manufacture, and test of the vehicle. This program should also define inspection techniques and procedures, accept-reject criteria, and requirements which must be met for substitute materials.

4.7.1 PHYSICAL PROPERTIES

Values for physical properties of structural materials shall be obtained from approved sources or determined by methods approved by NASA.

For additional information, refer to MIL-HDBK-5A, MIL-HDBK-17, and MIL-HDBK-23A.

4.7.2 ALLOWABLE MECHANICAL PROPERTIES

Values for allowable mechanical properties of structure and joints in their design environment (e.g., subjected to single stresses or combined stresses) shall be taken from sources approved by NASA, such as MIL-HDBK-5A, MIL-HDBK-17, and MIL-HDBK-23A. Where values for mechanical properties of new materials or joints and for properties of existing materials or joints in new environments are not available, they shall be determined by analytical or test methods approved by NASA. Where tests are required, they shall be of sufficient number to establish values for the mechanical properties on a statistical basis, and the tests shall conform to procedures in MIL-HDBK-5A and AFML-TR-66-386. Both "A" (99 percent nonexceedance with 95 percent confidence) and "B" (90 percent nonexceedance with 95 percent confidence) values for allowable stresses shall be provided.

The effects of temperature, thermal cycling and gradients, and detrimental environments shall be accounted for in defining allowable mechanical properties.

The modulus of elasticity and the yield and ultimate strengths of structural materials are usually reduced by increasing temperature. This effect is more pronounced with increased exposure time. The exposure with time may result in aging, overaging, recrystallization, alloy depletion, and solution of precipitated phases. In addition, corrosion resistance may be adversely affected by elevated temperatures. For materials used for cryogenic applications, the effect on the material brittleness should be accounted for.

4.7.2.1 STRUCTURAL COMPONENT ALLOWABLES

Material "A" allowable values shall be used in all applications where failure of a single load path would result in loss of structural integrity.

Material "B" allowable values may be used in redundant structure in which the failure of a component would result in a safe redistribution of applied loads to other load-carrying members.

Corrected allowable strength values for structural components should be determined from a comparison of the strength values from tests of coupons cut from the structural components and the "A" or "B" values cited in MIL-HDBK-5A.

4.7.2.2 FULL-SCALE ASSEMBLY ALLOWABLES

The allowable strength for assemblies under compressive loads shall be determined by test and shall be corrected in accordance with the procedures in MIL-HDBK-5A.

The procedures call for a correction factor to be applied based on compression tests on coupons taken from material in the structure and related to the minimum guaranteed properties for "A" or "B" values, as applicable.

The allowable strength for assemblies under tensile loads shall be determined by test. It shall be demonstrated that the material properties are at least equal to the appropriate guaranteed values given in MIL-HDBK-5A.

4.7.2.3 STRENGTH ALLOWABLES UNDER COMBINED LOADS

Combined stress interaction shall be accounted for in selecting values for mechanical properties of materials and simple initial buckling levels of components.

Interaction relationships, such as the reduction in values of strength allowables for attachment bolts under combined tension and shear, should be taken from MIL-HDBK-5A, where applicable. If allowable strength values for other load and stress combinations are not readily available, they should be analytically developed and substantiated or modified by tests.

4.7.3 FAILURE MECHANISMS

Materials from which the structure is fabricated shall not fail from cracking, corrosion, creep, impact, or irradiation during the service life of the vehicle.

4.7.3.1 FATIGUE

The fatigue-life characteristics of structural materials shall be determined by experiment for appropriate cyclic loading and temperature conditions.

Both crack-initiation and crack-propagation characteristics should be evaluated. It should be assumed that the fabricated structures contain flaws of the maximum size that cannot be detected by ordinary inspection procedures or by proof test. For the selected material, the number of stress cycles required to grow the maximum possible initial flaw to a size sufficient to initiate fracture should exceed the specified fatigue life, which is based on the specified service life. If it is suspected or known that the environment in which the structure operates will accelerate flaw growth, then this environment should be accounted for by analysis or test. For information on service life, refer to Section 4.8.

4.7.3.2 BRITTLE FRACTURE

The design of structure with thick sections shall account for the susceptibility of metals to brittle fracture. Fracture analyses shall be performed to determine critical flaw sizes, allowable initial flaw sizes, and probable fracture modes for candidate materials as they are intended to be used in the structure. Tests shall be performed to determine fracture toughness, flaw-growth characteristics, and threshold stress intensity of structural materials.

When possible, the metals selected for a given tension application should have sufficient fracture toughness at the intended operating temperatures so that the predicted critical sizes for surface and embedded flaws at the design-limit stress levels exceed the section thickness. The critical through-the-thickness crack lengths should be of a size easily detectable by ordinary inspection. When this is not possible, consideration should be given to the use of proof testing as a means of determining the possible existence of a flaw of critical size.

Values of allowable stresses for brittle nonmetallic materials such as ceramics shall be selected on a statistical basis, recognizing the scatter in the mechanical properties of these materials even when produced by closely controlled processes. Stress levels to be used with limit loads shall not permit the probability of failure of the component fabricated from these materials to exceed 10^{-6}.

It should be noted that brittle nonmetallic material design requires careful consideration of the effects of repeated loads, process control, nondestructive inspection, and proof testing on the selection of allowable stresses.

For recommended practices, refer to NASA SP-8040.

4.7.3.3 STRESS-CORROSION CRACKING

The sustained-stress crack-growth characteristics of the structural materials shall be determined by experiment for the anticipated service environments and at critical temperatures.

Stress-versus-time behavior should be examined both for material evidencing threshold stress and for material evidencing no threshold stress. In general, materials with threshold-stress values of less than 50 percent of the critical crack-intensity factor should be avoided. Materials with low threshold stresses should be allowed only when it can be shown by a "worst-case" fracture analysis that the use of low threshold stresses will not precipitate premature structural failure.

Alloys and other materials which are subjected to different heat-treat levels and temper and susceptible to stress-corrosion cracking under the anticipated environments (including cleaning and test fluids) should not be utilized, unless it can be shown by analysis or test that sustained surface-tensile stresses (from residual stresses, operating loads, assembly stresses, or any other source) are below the stress-corrosion cracking threshold-stress level for the specific environment, or that coatings are adequate to protect the metal from the environment. Metal fabrication techniques and material processes which avoid sustained residual surface-tensile stresses, stress concentrations, and the hazard of stress-corrosion cracking should be employed.

For recommended practices, refer to the forthcoming NASA special publication on stress-corrosion cracking.

4.7.3.4 HYDROGEN EMBRITTLEMENT

The design shall account for the susceptibility of structural materials to hydrogen-embrittlement failure.

Steels and titanium alloys are particularly susceptible to hydrogen embrittlement.

Where fabrication processes that can introduce hydrogen into the material are used, the material should be baked to eliminate the hydrogen. When experience does not substantiate the baking procedure employed, the adequacy of the procedure should be determined by

4.7.3.12 EUTECTIC MELTING

The design shall avoid eutectic melting of dissimilar materials which are joined by welding.

Consideration should be given to the reduction in ductility in welded joints that accompanies eutectic melting.

4.8 SERVICE LIFE

4.8.1 SAFE-LIFE

Safe-life design concepts shall be applied to all structure vital to the integrity of the vehicle or the safety of personnel. The safe-life shall be determined by analysis and test to be at least four times the specified service life.

The determination of structural safe-life shall take into consideration the effects of the following factors in combination with the expected operating environments:

- **Material properties and failure mechanisms**
- **Load spectra**
- **Cyclic-loads effects**
- **Sustained-loads effects**
- **Cumulative combined damage.**

For structure requiring a safe-life design, such as metallic pressure vessels or landing gears, any flaws that cannot be detected in a regularly scheduled inspection should not grow enough before the next scheduled inspection to degrade the strength of the structure below that required to sustain loads at temperatures defined by the limit-load and critical-temperature envelopes. Analysis of flaw growth should account for material properties, structural concepts, and operating stress levels throughout the structure, including adverse effects from variations in operational usage and environments. The inspection procedures should be considered adequate only when they can readily detect all flaws or defects greater than the allowable sizes.

4.8.2 FAIL-SAFE

Where practicable, fail-safe design concepts shall be applied.

For all fail-safe structure, the failure of a single principal structural component shall not degrade the strength or stiffness of the structure below that necessary to carry a specified percentage of limit load.

All fail-safe structure shall be accessible for periodic inspection.

Fail-safe analysis should consider: (1) size and source of flaws, (2) critical loading conditions and associated stress levels, (3) material properties, (4) critical structural components, (5) extent of damage which the structure can withstand, and (6) applicable modes of failure.

4.8.3 MATERIAL PROPERTIES

Material properties affecting the prediction of life shall be determined in accordance with the criteria of Sections 4.7.2 and 4.7.3.

Analysis of flaw growth shall account for material properties, loading conditions and associated stress levels, environmental conditions, and the size and source of flaws throughout the structure. The allowable size of flaws or defects shall be large enough to be detected by practical inspection procedures. The design shall be considered adequate only when inspection procedures permit ready detection of all flaws or defects greater than the allowable sizes.

4.8.4 LOAD SPECTRA

Load spectra shall be defined to represent analytically the cumulative static, dynamic, and environmental loads and deflections anticipated for all major structural components during the service life of the vehicle.

The load spectrum for each major structural component shall be determined by rational analysis which properly accounts for the following factors and their statistical variations:

- **Explicit definition of the model of vehicle usage upon which the life spectrum is based, considering as a minimum the conditions cited in Section 5.**
- **The frequency of application of the various types of loads and load levels.**
- **The frequency content, wave shape, and number of cycles of disturbances and vehicle responses.**
- **Environmentally induced loads.**
- **The environments acting simultaneously with loads.**

The spectrum shall be updated as usage measurements become available.

performing sustained threshold stress intensity tests, using precracked specimens. Where gaseous hydrogen is employed or where gaseous hydrogen comes in contact with metallic structure during vehicle operation, the susceptibility of the material to hydrogen embrittlement in the expected operating environments should be evaluated by tests using precracked sustained-stress specimens when applicable data are not available.

4.7.3.5 TEMPER EMBRITTLEMENT

The design shall account for susceptibility of alloy steels to temper embrittlement.

Alloy steels tempered in the temperature range of approximately 500° to 900°F are often prone to temper embrittlement resulting from grain-boundary precipitation phenomena. Alloy compositions and heat treatments must be carefully chosen to avoid this embrittlement. Tests should be made on representative samples to verify that temper embrittlement has not occurred.

4.7.3.6 CREEP

Materials shall be used which are resistant to creep. Materials shall not exhibit cumulative creep strain leading to rupture, detrimental deformation, or creep buckling of compression members during their service lives.

Analysis shall be supplemented by tests to verify the creep characteristics for the critical combinations of loads and temperatures for a specified time.

4.7.3.7 GENERAL (PITTING-TYPE) CORROSION

Materials shall resist general (pitting-type) corrosion and wear without degradation in strength in the expected operating environments.

Finishes and coatings should be used as needed to protect metal components.

The effects of material corrosion on the functioning of propulsion, control, and life-support systems shall be determined by test.

The vehicle structure should be designed to resist corrosion caused by atmospheric contaminants (e.g., salt air or automobile exhaust) during its service life.

4.7.3.8 GALVANIC CORROSION

Contacting materials subject to galvanic corrosion under the anticipated environmental conditions shall be avoided.

Relative positions in the galvanic series, the specific environment, the exposed areas, and use of electrically insulated joints should be considered. Where dissimilar metals must be in direct contact to meet electrical conductivity requirements, the joints should be sealed externally in such a manner as to prevent mutual contact of the two metals with an electrolyte.

4.7.3.9 METEOROID-IMPACT DAMAGE

The degradation of material properties (e.g., strength and ductility) caused by penetration, spallation, cratering, or erosion from meteoroid impact shall be accounted for.

For recommended practices, see NASA SP-8042.

4.7.3.10 RADIATION DAMAGE

The effects of exposure of materials to radiation from both external and onboard sources shall be determined and accounted for in design.

Exposure to electromagnetic and particulate radiation can degrade mechanical properties and surface characteristics of structural materials, especially of organic materials.

Recommended practices on protection against radiation damage are given in AFSC DH 3-2 (DN 4B4) and are to be given in forthcoming NASA special publications on effects of nuclear and space radiation on materials and on space radiation protection.

4.7.3.11 PROTECTIVE FINISHES AND SURFACE TREATMENTS

Finishes and treatments for metallic and nonmetallic surfaces of the vehicle shall be adequate to prevent detrimental degradation of structural strength under all environments occurring during the vehicle's service life.

Thermal-control coating materials shall account for degradation of the substrate or surrounding structure which might be caused by condensation, impingement, or sublimation from the coating, or by diffusion of coating or substrate elements.

The toxicity of outgassing products from heated coating materials shall be accounted for.

Use of coatings that may produce toxic or corrosive products shall be approved by NASA in advance.

For recommended practices, refer to MIL-A-8866(ASG), MIL-A-8867(ASG), ASD-TR-66-57, FAA-FAR Part 25, and AFSC DH 3-2 (Secs. 3A, 3B, and 3C).

4.8.5 CYCLIC LOADS

The design shall account for the effects of cyclic loads on the fatigue characteristics of the structure.

The fatigue characteristics of structural components and full-scale assemblies shall be determined by analysis and test. Combined loads and environments shall be accounted for, including static and dynamic loads, structural responses, temperature, vacuum, corrosion, and radiation.

4.8.6 SUSTAINED LOADS

The design shall account for creep-induced phenomena, including cracking and deformation of the vehicle structure. The allowable deformation and deflections shall be determined and it shall be demonstrated by analysis and test that the allowable values will not be exceeded in the service life of the structure.

Particular attention should be given to those materials which will be exposed for prolonged times to elevated temperatures under sustained loads to ensure that excessive deformation or actual rupture does not occur.

Flaw initiation or growth under sustained loads induced by such phenomena as stress-corrosion cracking, hydrogen-embrittlement cracking, and growth in high-stress inert environments shall be accounted for in the service-life prediction.

For all structure, it shall be demonstrated by analysis or test that the threshold stress intensities (K_{ISCC} or K_{TH} values) are sufficiently high to prevent flaw growth during the service life. The K_{ISCC} or K_{TH} values shall be determined for the representative environment and temperature conditions. (These values are defined as follows: K_{ISCC} is the critical stress intensity for opening-mode cracking, Mode I, in corrosive environmental conditions, and K_{TH} is the threshold value of the stress-intensity factor.)

4.8.7 CUMULATIVE COMBINED DAMAGE

Structural service-life predictions shall account for the effects of cumulative combined cyclic and sustained loads under the environmental conditions expected in service.

For information on load spectra, refer to Sections 4.8.4 and 5.1.4.

4.8.7.1 METALLIC PRESSURE VESSELS

Flaw growth shall not exceed the growth required to increase the maximum undetectable initial flaw to a size where the stress intensity under limit-stress levels exceeds the threshold stress-intensity values. The effects of short-time load excursions which result in stress intensities above the threshold (e.g., due to maneuver loads, vibratory loads, or gust loads) shall be accounted for in the fatigue-life predictions.

Data on sustained-load flaw-growth rates and on fatigue-crack-growth rates should be developed for the structural materials as a function of frequency-and-load ratio in the anticipated service environments.

For pressure vessels susceptible to combined creep deformations and cyclic fatigue loading, the combined effects shall be experimentally determined and accounted for in the service-life predictions.

For metallic pressure vessels not carrying vehicle loads, flaw growth shall be accounted for by the practices set forth in NASA SP-8040.

The use of the fracture-mechanics concept (NASA SP-8040) has not been completely substantiated for metallic pressure vessels carrying vehicle loads.

4.8.7.2 GENERAL STRUCTURE

The combined effects of fatigue, thermal stress, and creep on general structure shall be evaluated.

In lieu of full-scale vehicle or built-up structural assembly tests, the service life of the structure may be estimated by rational cumulative-damage methods.

4.9 INTERFACE COMPATIBILITY

The vehicle structure shall be physically and mechanically compatible with functional components, assemblies, systems, fluids, and gases. The design shall account for: (1) direct physical interaction of vehicle structure and components, assemblies, and systems; and (2) indirect interaction of the vehicle with two or more components, assemblies, or systems. Interface compatibility shall be verified by experiment.

Although interface compatibility is considered in various sections of this document, the most important interfaces are also noted in the following paragraphs.

4.9.1 STRUCTURAL INTERACTIONS WITHIN BOOSTER OR ORBITER

4.9.1.1 PERSONNEL AND THE LIFE-SUPPORT SYSTEM

Structural design shall be compatible with the constraints imposed by personnel and the life-support system.

Constraints include physiological limits on noise, vibration, shock, and load levels, provision for appropriate hand holds, and restraint points for performing manual operations.

4.9.1.2 ELECTRONIC AND ELECTRICAL SYSTEMS

Structural design shall provide a unipotential structure and freedom from radio-frequency interference.

An electrical connection should be provided between equipment mounts and cases and the unipotential structure which has sufficient strength to withstand applied loading and shock and vibration environments.

4.9.1.3 POWER SYSTEM

The vehicle structure shall be designed to withstand the effects of integration of the power system, including all power-system-induced environments, loads, and configuration interactions. The mechanical, fluid, thermal, and radiation environments and loads generated by the power system for all mission phases shall be identified and accounted for in the design.

4.9.1.4 PROPULSION SYSTEM

The vehicle structure shall be designed to withstand the effects of integration of the propulsion system, including all propulsion-system-induced environments, loads, and configuration interactions.

4.9.1.5 GUIDANCE AND CONTROL SYSTEM

The vehicle structure shall be designed to withstand the effects of integration with the guidance and control system. All control-surface structures, including hinges and brackets, shall be designed fail-safe. The structure shall be strong enough to withstand the loads resulting from:

1. **Surface displacements at the maximum rate capability of the power-control system.**
2. **Surface displacements at the maximum deflection, limited by the stops.**
3. **Available hinge moment.**
4. **Electronic logic.**

For recommended practices, refer to NASA SP-8036.

4.9.1.6 THERMAL PROTECTION SYSTEM

All structural thermal-protection-system interface components shall be designed so that differential thermal-expansion effects are adequately accounted for. Provisions for sealing to avoid high-enthalpy gas flow shall be made, when necessary.

The structural thermal-protection-system interface components shall be designed to withstand aerodynamic, acoustic, vibration, and shock loadings under all expected operating environments. In addition, these interface components shall be designed so that panel flutter is prevented. The structural evaluation shall consider at least the following parameters: (1) panel-support-bracket spacing, (2) panel-support stiffness, and (3) panel-edge rotational constraints imposed by support brackets.

4.9.1.7 PAYLOAD

The design shall prevent payloads from impairing the vehicle's structural integrity or control-system stability.

Clearance shall be maintained between the specified dynamic envelope of payload volume and the cargo compartment under all loading and environmental conditions.

Payload-support structure shall be designed to accommodate the range of shapes of payloads and their attach-point locations which are specified by NASA, and to prevent transmission of loads which exceed the maximum levels specified for the payload.

The design of the cargo compartment, including doors, rails, and payload-support structure, shall account for the requirements for handling, loading, and unloading the payload in orbit and on the ground.

4.9.1.8 GROUND SUPPORT EQUIPMENT

Vehicle structure shall be designed to withstand loads induced by ground support equipment and the related handling, transportation, and storage environments.

Although it is an objective that the design of structure other than pressure vessels be based only upon critical flight, landing, and takeoff conditions (Sec. 3.2), the foregoing criterion should be applied with the concurrence of NASA in the event the objective cannot be met.

4.9.1.9 STRUCTURE-FLUID COMPATIBILITY

The materials employed in the structural design shall be compatible with propellants used in the vehicle.

Fluids used for cleaning, lubricating, or proof-testing vehicle structure (e.g., tanks, pressure vessels, plumbing, or highly stressed parts) shall be compatible with structural materials.

4.9.1.10 REFURBISHMENT

Structural materials shall be compatible with the processes and materials used in refurbishment.

4.9.2 STRUCTURAL INTERACTIONS BETWEEN MATED VEHICLES

Physical interfaces between mated vehicles and required clearances between booster and orbiter shall be identified and accounted for in vehicle design.

4.9.2.1 LOADS

The structure of mated vehicles shall be designed to withstand the loads and environments induced by either vehicle during all mission phases. Loading and temperature-induced deformations that may cause loading across interfaces or restrict clearances shall be determined and accounted for in the design.

The following noise and vibration environments shall be evaluated: (1) booster-engine exhaust-stream turbulent mixing; (2) turbulent boundary-layer noise resulting from convection of random-sized eddies along the vehicle surfaces; (3) interaction of shocks and turbulent boundary layer; (4) primary impact and reflection of compression and expansion shocks on vehicle surfaces; and (5) wake excitations. Account shall be taken of booster propulsion-system configuration, launch-pad and exhaust-deflector configuration, ascent trajectories, and composite vehicle-profile shape.

Shock evaluation of the mated vehicles shall include the following: (1) engine-ignition and -shutdown impulses; (2) impulses resulting from activation of vehicle primary-separation mechanisms; (3) shocks resulting from handling, matings, and transportation in the mated condition; and (4) detonation of pyrotechnic devices.

4.9.2.2 PRESSURES

The design shall account for nonregulated pressures induced by the mated vehicles.

Design practices should be followed which minimize the effects of detrimental nonregulated pressures, such as lateral venting.

4.9.2.3 STATIC ELASTICITY

Effects induced by mated vehicles shall be accounted for in all static-elasticity investigations.

The investigations should consider all loads, temperatures, and other environments from mating which result in more severe design conditions. Accumulated deformations incurred in successive missions should be anticipated and accounted for in the design.

4.9.2.4 DYNAMIC ELASTICITY

The design shall account for dynamic-elasticity interactions between the mated vehicles. The effect of the products of inertia of the mated-vehicle configuration on control-system capability shall be evaluated, including the induced accelerations and motions occurring during the time lag between applied and correctional forces.

Mated configurations may have an unsymmetrical profile, resulting in extremely large products of inertia. Forces applied in any plane other than the profile plane may therefore induce very significant accelerations in mutually perpendicular planes. Any appreciable time lag between applied and correctional forces may result in uncontrollable unstable motions. The time lag should include the time involved in deflecting the structure to provide the reaction to the corrective forces. Tests should be made on mated vehicles to verify analytical results.

4.9.2.5 THERMAL CHARACTERISTICS

Mated vehicles and their interconnecting structure shall be designed to withstand gross and local heating effects caused or induced by the proximity of each vehicle to the other.

The design shall account for heat exchange between mated vehicles from aerodynamic and propulsion-system heating and cryogenics, and for heat exchange between systems in one vehicle.

4.9.2.6 CLEARANCE

The design shall provide adequate clearance between the booster and orbiter to prevent functional interference.

Accumulated deformations resulting from successive missions shall be anticipated and accounted for in the

design. Loading and temperature-induced deformations that may induce loading across interfaces or restrict clearances shall be determined and considered in the design. Dynamic-response effects of mated and proximate vehicles shall be determined and accounted for in the design.

4.9.3 STRUCTURAL INTERACTIONS WITH EXTERNAL SPACE VEHICLES

The vehicle and its interconnecting structures shall be designed to withstand the loads and environments encountered during docking and undocking, and while in the mated condition with external space vehicles. Evaluation shall include at least the following factors: (1) relative vehicle displacement, velocity, and acceleration; (2) vehicle inertial and elastic properties; (3) docking-mechanism forces; (4) seal flexibility; and (5) fluid effects.

Forces should be limited or otherwise controlled so that vehicle motions can be stabilized by control systems and the structural and functional capability of all vehicle systems remains intact.

4.10 SUPPLEMENTARY CHARACTERISTICS

4.10.1 DESIGN THICKNESS

The structural design thickness, t_d, for each metallic structural member other than mechanically or chemically milled pressure vessels shall be the minimum thickness obtained by either of the following relationships:

t_d = mean thickness based on equal plus and minus tolerances

or

t_d = N times the minimum thickness

where

N = 1.10 for strength design

N = 1.05 for stability design

The mean and minimum design thicknesses, as used above, shall include allowances for cumulative material damage or loss resulting from repeated exposure to the design environment. The design thickness for mechanically or chemically milled pressure vessels shall be the minimum thickness (i.e., mean minus the lower tolerance).

Design thickness for nonmetallic structural members shall be based on rational analysis.

The design thickness for ablation material shall be increased by 25 percent of the predicted geometric thickness lost through ablation to account for uncertainties in thermochemical ablation properties of the material. No factor or increase shall be applied to the remaining thickness required for insulation.

4.10.2 SAFETY

Structural design shall account for the safety requirements imposed by NASA and the test range from which the vehicle is launched.

Of principal concern are hazards faced by personnel during the storage, assembly, refurbishment, field test, launch, and flight of space vehicles. Personnel safety should be considered by use of the following design practices: (1) minimum proof factors for pressurized structure; (2) constraints on using or handling explosive, toxic, incendiary, or radioactive materials; (3) provisions for escape, access, and flight termination in the event of system malfunction; and (4) provisions to prevent unsafe or undesirable effects from magnetic fields, static electricity, nuclear radiation, heat transfer, vibration, and shock.

The compartments for personnel shall not utilize materials which present a hazard of a noxious or toxic nature under the expected operating environments. For other portions of the structure, adequate protective covers over wiring and plumbing, fire walls, or other equipment shall be provided to control or inhibit the propagation of fire.

4.10.3 LEAKAGE

Pressurized structure shall be designed so that any leakage occurring during a mission will permit successful completion of the mission. For pressurized structure where a specified pressure must be maintained, leakage rates shall be established experimentally for structural joints, seals around doors and access hatches, skin penetrations, and pressure fittings.

In no case shall leakage exceed levels stated in safety requirements for toxic and explosive fluids, or levels which might jeopardize system function or rated life.

4.10.4 VENTING

All compartments other than pressure vessels shall be analyzed to determine that the pressure differentials across all compartment walls and the compartment environment are restricted within allowable limits. Adequate venting of compartments (including interstages, payload shrouds, fairings, heat shields, housings for electronic equipment, conduits, and insulation panels) shall be provided to restrict these pressure differentials. Otherwise, the walls of the compartment for which no venting is provided shall be designed to withstand the maximum attainable pressure differentials. The adequacy of vents for meeting all vehicle and system requirements shall be verified by analysis or test, or combinations of both.

If sandwich panels are vented, consideration should be given to the possibility of a mechanically induced failure due to freezing of ingested moisture. If sandwich panels are unvented, the magnitude of the differential pressures across the skins may be limited by use of an internal vacuum or an inert gas.

Vents shall neither induce undesirable aerodynamic effects on the vehicle nor restrict trajectories under which the vehicle may be operated.

The design of compartment vents shall, as a minimum, account for the following requirements and constraints, as applicable: (1) the effects of vent fluid injected into the compartment on equipment in the compartment; (2) the environment needed for compartment equipment; (3) compatibility with prelaunch and launch gas-flow systems (e.g., ground air conditioning, insulation purging, and propellant-fume ventilation); (4) the interaction of the ejected fluid with the external flow fluid; (5) the strength and structural characteristics of the compartment walls (including panel flutter and response to random noise); and (6) the strength and structural characteristics of equipment in the compartment.

Recommended practices are to be presented in a forthcoming NASA special publication on compartment venting.

Pressure vessels shall be designed to withstand internal pressures which are lower than the ambient external pressure if provision is not made to prevent a collapsing pressure differential from existing during tank emptying. See objective of Section 3.9.

4.10.5 MECHANICAL COMPONENTS

Doors and Windows. Doors and windows shall be designed to withstand: (1) the maximum pressure differential across them; (2) thermal loads and thermal gradients; and (3) static and dynamic loads. The window installations and the surrounding structure shall be designed to prevent loading of the windows induced by adjacent structural loads and deformations, and to accommodate differential thermal expansion. Window covers shall be designed to avoid imposing increased heating rates on surrounding structure.

Doors and windows shall remain in place and locks and actuating mechanisms shall not unlatch under ultimate design conditions.

Mechanical backlash shall be minimized.

4.10.6 DECELERATION DEVICES

The decelerator system shall be considered to be a structural system subject to the same criteria as hard structure. Aerodynamic decelerator devices shall be designed to decelerate, stabilize, and control the descent of the spacecraft in the service environment within prescribed limits without imposing detrimental deformations, vibrations, or impact shocks on the spacecraft. Loads and stresses imposed by deployment shall be determined by analysis and test. Loads and stresses induced in the deployable decelerator device shall be determined by analysis and test.

Structural-design factors, including safety factors, shall be defined and applied to the decelerator to account for known deleterious phenomena such as abrasion, fatigue, humidity, vacuum, radiation, joint efficiency, nonuniform loading, line convergence, and material-property degradation due to temperature.

4.10.7 METEOROID PROTECTION

The probability of unacceptable damage from meteoroid impact shall be specified and the vehicle shall be designed so that this probability is not exceeded.

The vehicle shall be designed to prevent meteoroid damage to structure or components which could impair flightworthiness or reduce the service life within the prescribed probability.

Analysis should account for shock loads resulting from particle impact which may induce spallation or cracking. The design of pressure vessels containing fluids should account for pressure pulses resulting from meteoroid impact, which, when transmitted through the fluid, can cause structural failure of the vessel.

The meteoroid environment and the structural response to meteoroid impact are not precisely known, particularly for the more complicated multiwall structures. These unknowns reduce the confidence in calculated reliabilities. Perhaps some method of repairing noncatastrophic holes in enclosures for personnel should be considered during design, inasmuch as an emergency repair capability could enhance the reliability of the design.

4.10.8 RADIATION PROTECTION

Radiation shielding shall be provided if the inherent protection afforded by the vehicle design is not sufficient to prevent the allowable radiation doses and dose rates from being exceeded for the duration of each mission. When provided, shielding shall be compatible with the combined radiation, thermal, and mechanical environments.

4.10.9 CRASHWORTHINESS AND DITCHING

Seats, harness-support structure, equipment-support structure (e.g., instrumentation, cargo, engines, or fuel tanks), mechanisms for holding canopies and doors in their open positions, and any other items whose failure could result in injury to personnel during a crash or prevent egress from the crashed vehicle shall be designed to resist crash loads.

Ditching loads applied to the structure shall not cause structural failure which would make the vehicle submerge rapidly, injure the personnel, or in any other way prevent the personnel from making a satisfactory escape from the ditched vehicle.

Structural requirements for crash landing on land or water will depend strongly on an evaluation of the relationship between vehicle weight and risk. It is expected, however, that if structural crashworthiness requirements are specified, they will only provide local structure with sufficient strength to prevent failures which will reduce the chance of effecting a safe escape for all personnel.

4.10.10 ANTENNAS

Antennas shall be designed to withstand the anticipated static and dynamic loads and environments through the mission.

Antennas shall be designed to prevent detrimental coupling with the vehicle structure or vehicle control system at any stage of deployment.

If antennas are retractable, deployable, or movable, their operating characteristics shall not be impaired by use or by the environment.

If protective antenna windows are employed, the window material shall be compatible with the surrounding structure and the thermal protection system. The design shall be insensitive to the degradation of functional properties due to induced loads or deflections.

4.10.11 CASTINGS

Only high-quality castings shall be utilized for structural components. The use of castings in primary structural components shall be subject to NASA approval. At least one sample of each casting design shall be qualified to ultimate load level at critical temperature. All castings shall be subjected to acceptance testing to limit load at critical temperature.

4.10.12 FRICTION AND WEAR

All contacting surfaces designed to undergo a sliding or rolling motion shall be lubricated.

When available data are not applicable, tests shall be conducted to demonstrate that the friction and wear characteristics are acceptable and in accordance with analytical predictions.

It shall be demonstrated by analysis and test that actual friction forces will not exceed the limitations of available power, and that actual wear will not impair the functional performance of sliding or rolling surfaces.

The performance of lubricants shall not be degraded below minimum design requirements as a result of multiple exposures to service environments such as high temperature, vacuum, pressure, propellants, purge gases, moisture, or contaminants. Where exposure to the environments could be expected to degrade performance of seals and lubricants, adequate protection systems shall be provided. Design provisions shall be made for inspection, refurbishment, maintenance, and replacement of

the protection systems, as appropriate, to ensure effectiveness throughout the service life of the contacting surfaces.

4.10.13 REFURBISHMENT

The life expectancy of refurbished components shall be compatible with the intended reuse cycle. Distortions and protrusions shall be no greater than the tolerances specified for the original configuration. Refurbished components shall meet acceptance specifications for new parts.

4.10.14 LANDING GEAR

The landing gear and supporting structure shall be designed to withstand the appropriate design environments, including the residual temperatures from entry. The landing-gear doors shall provide the prescribed thermal protection and shall be capable of reopening after entry.

4.10.15 COMPOSITE, BONDED, AND BRAZED CONSTRUCTION

Procedures shall be devised for reliable detection of flaws in composite, bonded, and brazed construction. Nondestructive testing of all bonded and brazed sandwich and composite structure shall be performed in accordance with a plan approved by NASA.

4.10.16 REWELDS

Rewelding shall not reduce the probability of successfully completing the mission. Materials and procedures employed for the rewelding of space-vehicle structure shall be approved by NASA.

4.10.17 FASTENER REUSE

The probability of successfully completing the mission shall not be reduced by requirements for reuse of fasteners. The type and location of critical fasteners and the conditions for reuse shall be specified.

Confidence in the reusability of fasteners depends on load level, degree of redundancy, degree of inspection, and procedural controls on installation and use.

5. DESIGN CONDITIONS

5.1 GENERAL CONDITIONS

5.1.1 LOADS AND PRESSURES

All static and dynamic loads and pressures (external and internal) which may affect yield and ultimate strength, material properties, stresses, and deflections shall be defined and accounted for. The effects of thermal and elastic structural deflections, allowable structural and thrust-vector misalignments, and structural offsets and dimensional tolerances shall be included in analyses of all loads, load distributions, and structural adequacy.

Loads shall be distributed internally throughout the structure by rational analyses which include the effects of structural nonlinearities and temperature gradients.

Analyses of dynamic loads shall include all significant changes in vehicle mass properties with time, all significant structural flexibilities and damping, and all significant load spectra. These analyses shall account for coupling of the vehicle with the launcher during static test firings and during normal operation.

Recommended practices for analytically modeling the structure to determine the mode shapes, frequencies, and damping are given in NASA SP-8012.

All significant loads and pressures identified for each of the life phases and events in Section 5.2 shall be accounted for. In addition, loads and pressures induced by liquid slosh, noise, vibration and shock, and buffeting during several phases of the vehicle's service life shall be accounted for.

Additional conditions that should be accounted for in only one life phase are identified, as appropriate, in Sections 5.2.5 through 5.2.12.

5.1.1.1 SLOSH

Slosh loads for individual tank and baffle elements shall be accounted for and shall include, as a minimum, the effects of the physical properties of the liquid, the liquid level, and acceleration.

The theoretical and experimental design data presented in NASA SP-8009 can be used to check space-shuttle system designs for structural adequacy if the data are applicable, but tests should be conducted when existing information is not applicable to the tank or baffle designs. These tests shall simulate the natural slosh frequencies, effective liquid damping, and slosh loads on the tank and baffle system. For recommended practices, refer to NASA SP-8009 and SP-8031.

5.1.1.2 NOISE

Noise excitation from aerodynamic sources (e.g., base pressure and turbulent boundary-layer pressure fluctuations) occurring during ascent, entry, and atmospheric flight shall be accounted for. Noise excitation from other sources internal and external to the vehicle shall be accounted for during all phases of the vehicle's service life.

The characteristics of the acoustic-pressure fields imposed by the propulsion systems shall be established and accounted for, including the effects of:

- Free jet mass flow
- Effective exit velocity and density
- Nozzle exit-plane diameter
- Characteristics of the medium into which the exhaust gases flow
- Distances and shapes of nearby surfaces (e.g., launcher and ground)
- Combustion processes in the jet stream
- Pressure of strong shock waves in the jet.

5.1.1.3 VIBRATION AND SHOCK

At least the following life phases and events shall be evaluated for potentially critical vibration and shock loads: (1) manufacturing, (2) transportation and ground handling, (3) static or captive firings, (4) motor or engine ignition and shutdown, (5) launch-stand release, (6) separation and abort, (7) docking and cargo transfer, (8) maneuvering, (9) deployment of recovery and landing devices, and (10) landing impact.

Recommended practices for analyzing, evaluating, and alleviating the response to vibration and shock loadings are treated in NASA SP-8046 and in forthcoming NASA

special publications on mechanical shock response analysis, protection against explosive shock, and structural vibration prediction.

5.1.1.4 BUFFETING

Low-frequency buffeting effects shall be examined in which gross bending response of the mated or unmated vehicle is produced by separated flow or rocket-exhaust plume. High-frequency buffet loads resulting from local impingement of a turbulent flow shall be accounted for to prevent damage to structure or internal components.

The evaluation of buffeting effects should consider both local and overall vehicle response and stability, and should account for such factors as aerodynamic interference, vehicle cross-section shape and area changes, protuberances, and structural flexibility.

For recommended practices, refer to NASA SP-8001.

5.1.2 HEAT TRANSFER

All thermal energy-transfer conditions which may influence yield and ultimate strength, material properties, stresses, and deflections shall be defined and accounted for. At least the following conditions shall be evaluated: (1) gasdynamic heating; (2) solar and planetary thermal radiation; (3) structural reradiation and conduction; and (4) internally induced heat transfer.

5.1.2.1 GASDYNAMIC HEATING

The external inviscid-flow fields shall be defined during launch, ascent, and entry, and evaluations made of the magnitude of the aerodynamic and rocket-exhaust-plume heat transfer to the structure. When analysis indicates a critical effect of aerodynamic or rocket-exhaust-plume heating on design, and when existing experimental information is not applicable to the design configuration or operational conditions, tests shall be conducted to evaluate the external heating sources in at least the following: (1) areas adjacent to protuberances; (2) wake areas downstream of protuberances; (3) separated-flow and reattachment areas; (4) shock-wave impingement areas; (5) areas of base heating; and (6) areas subjected to three-dimensional exhaust plumes or to plume impingement.

For recommended practices, see NASA SP-8014, SP-8029, and a forthcoming NASA special publication on entry gasdynamic heating.

The analytical models for the inviscid-flow field required for gasdynamic heating analyses shall, as a minimum, include: (1) the effects of vehicle attitude and shape on the inviscid-flow properties; (2) the effects of viscous interaction, mass transfer, and radiative cooling on the inviscid-flow properties; (3) appropriate thermodynamic, transport, and optical properties; and (4) finite-rate chemistry.

5.1.2.1.1 AERODYNAMIC

The convective-heat transfer and shear calculations shall include the effects of: (1) low-density flow, (2) continuum flow, (3) appropriate thermodynamic and transport properties, (4) complex flow regions, (5) boundary-layer transition, (6) mass transfer, and (7) finite-rate chemistry.

In the prediction of convective heating, laminar, turbulent, and transitional boundary layers and the effects of surface roughness and interference shall be considered. Nominal best estimates of heating in the presence of these effects shall be modified by appropriate factors to yield the required probability values. The factors shall be based on the particular design requirements and the type of thermal protection system used. In addition, convective-heating predictions shall include the effects of structural thermal distortions through the induced inviscid-flow field. Extrapolations from heating rates measured in ground test facilities to flight predictions shall account for real-gas effects and any ground test deficiencies in Mach number, Reynolds number, temperature ratios, and enthalpy levels.

As an interim method, in lieu of probability values, uncertainty factors on heat-transfer coefficients for laminar, turbulent, or interference heating should be applied independently. The uncertainty factors to be used initially to obtain heat-transfer coefficients are:

Laminar heating	1.10
Turbulent heating	1.25
Heating in interference and separated flow areas	1.5

In regions of localized roughness elements, the heat-transfer coefficient will include a correction to account for surface roughness. The method given in AIAA Paper No. 67-164 may be used to obtain the roughness correction factor. With the roughness criteria of Section 4.6, it is anticipated that this factor will not exceed 1.25 for metallic heat-shield areas. As indicated in Section 4.2, no factor or tolerance should be applied to predicted temperatures or temperature gradients.

Practices shall be defined, subject to NASA approval, for predicting transition from laminar to turbulent boundary-layer flow, accounting for effects of local Mach number, unit Reynolds number, wall temperature, and vehicle configuration. Such practices shall include a means of predicting turbulent overshoot heating.

The radiative-heat-transfer calculations shall include the effects of radiative cooling, nongray self-absorption, appropriate thermodynamic and optical properties, mass transfer, and nonequilibrium flow.

Detailed calculations of radiative heat transfer, including each of the effects listed in the preceding criterion, are time-consuming and difficult. It is therefore recommended that simplified conservative calculations be performed for several altitudes and vehicle locations to indicate whether radiative heating is significant. If significant radiative heating is found, more detailed analyses should be performed.

5.1.2.1.2 ROCKET-EXHAUST PLUME

The rocket-exhaust-plume heating analysis shall include the influence of the vehicle's external flow field, nozzle configuration, propellant composition, and chamber pressure, as well as the effects of local geometry and upstream geometry, base geometry and engine gimbaling, engine-out condition, secondary combustions and other chemical reactions, the adjacent launch-pad structure, and base or engine-compartment venting.

5.1.2.2 SOLAR AND PLANETARY THERMAL RADIATION

Direct solar radiation (insolation) and solar radiation reflected from earth, moon, and objects in interlunar space (albedo) shall be evaluated for the space phase of the orbiter. Insolation shall also be evaluated for the prelaunch and launch phases. The effects of the following on temperature distributions in the vehicle shall be determined: vehicle orientation (i.e., the time-varying geometric relationship between the vehicle and the heat sources), vehicle configuration, and absorptance and emittance of vehicle surfaces.

5.1.2.3 STRUCTURAL RERADIATION AND CONDUCTION

The thermal energy radiated by structural surfaces to other structural surfaces and to space, and the thermal energy conducted through structural components and through structural joints shall be accounted for.

5.1.2.4 INTERNALLY INDUCED HEAT TRANSFER

Heat transfer between the structure and engines, cryogens, environmental control systems, and internal equipment shall be evaluated, as appropriate. The effects of at least the following on the temperature distributions within the cryogen-containment system and on its adjacent structure shall be determined:

- Cryogen loading at the maximum rate and the transient temperature distribution in the containment-system wall.
- Temperature variations in the loaded containment system due to liquid level and thermal stratification in the cryogenic liquid (including vapor in the ullage space).
- Warm gas injected locally into the tank, if any.
- Uncertainties in liquid position within the containment system, in the absence of gravity or inertial forces.
- Extreme variations in tank warmup histories, based on the residual propellants for 99 percent engine-burnout conditions.
- Cooldown resulting from gas expansion during venting or pressure reduction.
- Any other phenomenon resulting in temperatures differing significantly from the temperature of the contained bulk liquid.

When a component is critical at maximum internal temperature, the temperature shall be based on conservative assumptions from the preceding conditions, on rational analysis, or, if the range of uncertainty in the analysis is significant to the design, on testing. When a component is critical at minimum internal temperature, the minimum bulk temperature of the contained cryogen shall be used, unless a higher minimum can be proven.

5.1.2.5 STRUCTURAL DESIGN TEMPERATURES

During ground phases, external heat transfer shall be determined, using mutually related values of properties of the natural environment which yield 99 percent probability maximum or minimum values of external surface temperature, whichever is critical. During flight phases, external heat transfer shall be determined, using the design trajectories specified for each mission phase. External and internal convective-heat-transfer coefficients shall be multiplied by uncertainty factors to yield 99 percent probability maximum or minimum values, whichever is critical. In the formulation of these factors, the effects of the 99th percentile values of material

thermal properties, structural dimensions, joint conductance, and/or total panel conductance shall be combined, using a root-sum-squared technique to yield design temperatures.**

Where sufficient test data are not available, conservative values may be utilized, subject to NASA approval.

Structural temperatures shall be determined after landing for a sufficient period of time to establish peak values of temperature and loads and stresses induced by heating applied during entry.

Critical temperature conditions for some structural components may occur after landing because of soak-through of stored heat. Ground cooling offers a possible means of maintaining peak values below flight levels.

5.1.3 APPLICATION OF NATURAL AND MAN-MADE ENVIRONMENTS

The effects on the structure of the environments shown in table 5-1 shall be evaluated for each phase of the vehicle's life indicated. The structure shall exhibit all of the characteristics identified in Section 4 after exposure to these environments.

The following paragraphs provide additional criteria and pertinent information on specific environments to avoid unnecessary repetition in subsequent subsections:

Rain and Hail. Certain thermal-protection-system materials may incur significant rain or hail damage. Particularly susceptible are reusable external insulation, coatings for metallic heat shields, and the thin metallic heat shields themselves.

Electromagnetic Radiation. **Electromagnetic and particulate radiation from onboard vehicle sources and from the natural environment shall be accounted for. The effect of both dose rates and integrated doses on each potentially critical component over its life cycle shall be evaluated, accounting for the following factors, as applicable: (1) spectral, temporal, and directional characteristics of each primary and secondary radiation**

TABLE 5-1 STRUCTURAL ENVIRONMENTS

LIFE PHASE \ ENVIRONMENT	ATMOSPHERIC PROPERTIES	WINDS AND GUSTS	RAIN	HAIL	BLOWING SAND AND DUST	SALT AIR	HUMIDITY	FUNGUS	ATMOSPHERIC CONTAMINANTS	ATMOSPHERIC ELECTRICITY	SOLAR THERMAL RADIATION	ALBEDO	ELECTRO-RADIATION	METEOROIDS	NOISE	RUNWAY AND TAXIWAY ROUGHNESS
Manufacturing	X				X		X		X							
Storage	X	X	X	X	X	X	X	X	X	X						
Transportation and ground handling	X	X	X	X	X	X	X		X	X						X
Prelaunch	X	X	X		X	X	X		X	X	X					
Launch	X	X	X				X			X	X				X	
Ascent	X	X	X		X					X					X	
Space											X	X	X	X	X	
Entry	X	X	X							X					X	
Atmospheric flight	X	X	X	X	X	X	X		X	X					X	
Landing and horizontal takeoff	X	X	X	X		X	X		X	X					X	X

involved; (2) modification of the radiation environment or its effects by other environmental phenomena; (3) spatial distribution and composition of the vehicle mass and its contents; (4) time-dependence of significant masses and their locations (e.g., propellant, cargo, equipment, and jettisonable structure, if any); and (5) the finite extent of surfaces or volumes of potentially critical components and systems.

Meteoroid Impact. The degree of structural damage expected from meteoroid impact shall be determined by analysis and experiment. The damage assessment shall, as a minimum, include the types of failure of the components indicated in table 5-2.

The type and degree of expected damage from meteoroid impact shall be substantiated by appropriate tests.

5.1.4 LOAD SPECTRA

All the conditions identified in Section 5 shall be included in the definition of the load spectra. (See Section 4.8.4.)

5.2 SERVICE CONDITIONS

5.2.1 LIFE PHASES AND EVENTS

At least the following phases in the life of the shuttle vehicles shall be investigated for critical loads, pressures, temperatures, and structural response: (1) manufacturing, (2) storage, (3) transportation and ground handling, (4) prelaunch, (5) launch, (6) ascent, (7) space, (8) entry, (9) atmospheric flight, (10) landing and horizontal takeoff, and (11) emergency. Unless otherwise specified or required for safety, the service conditions, loads, and environmental phenomena associated with all ground activity other than landing and takeoff shall not control the design of the flight structure, except in local areas around attachment points.

All structural weight penalties or special requirements for handling equipment imposed on the vehicle by safety constraints or by preflight events and phenomena should be identified and submitted to NASA for approval.

TABLE 5-2 **PROBABLE FAILURE FROM METEOROID DAMAGE**

PROBABLE CRITICAL TYPES OF FAILURE	PRESSURE CABINS	TANKS	RADIATORS	WINDOWS	SPECIAL-PURPOSE SURFACES	ENTRY THERMAL PROTECTION*
Catastrophic rupture	X	X		X		
Secondary fractures			X			
Leakage	X	X	X			
Vaporific flash	X					
Deflagration		X				
Deformation			X			
Reduced residual strength	X	X	X	X	X	
Fluid contamination		X	X			
Thermal insulation damage	X	X				X
Obscuration				X		
Erosion				X	X	

*Varies with the specific thermal protection system.

5.2.2 MANUFACTURING

Fabrication and assembly operations shall be evaluated for (1) critical stress conditions from material handling; (2) forming, stretching, or other fabrication process; (3) clamping, misfit, and misalignments during assembly; (4) welding and welding repair, and (5) factory-checkout operations, including pressurization cycles.

Effects of natural and induced environments on thermal coatings and on the strength and durability of bonding compounds or bonded structure shall be evaluated.

The loads from hoisting and assembly shall be determined, using the transportation and ground handling load factors and conditions given in Section 5.2.4.1.

5.2.3 STORAGE

Loads and environments which the vehicle structure may experience during storage shall be accounted for or the structure shall be protected against them. At least the following shall be considered:

1. **Pressure-differential loads, including the effects of venting.**
2. **Natural and man-made environments.** (Refer to Section 5.1.3 for specific environments.)
3. **Environments and loads from stored propellants and fluids, considering pressure and temperature as well as chemical and physical effects on structural materials and adhesives.**

5.2.4 TRANSPORTATION AND GROUND HANDLING

During transportation and ground handling, the effects of static and dynamic loads and natural and man-made environments on the vehicle strength and fatigue characteristics shall be evaluated.

Load oscillations should be counted and load amplitude should be measured and evaluated for all fatigue-critical structure. It may be necessary to monitor the handling and transportation loads on production vehicles to ensure that the actual loads are within acceptable limits. Rational analyses should be performed to determine the need for such monitoring.

For recommended practices, refer to the forthcoming NASA special publication on transportation and handling loads.

5.2.4.1 LOADS

The body axes and positive directions indicated in figure 5-1 are used in this section for transportation and ground handling loads. Corresponding inertial loads are in the opposite direction.

5.2.4.1.1 TRANSPORTATION

The limit-load factors for transportation of components presented in table 5-3 shall be applied at the support points of the transporting vehicle.

5.2.4.1.2 TOWING

The limit towing loads shall be as defined in table 5-4 and figure 5-2, based on the maximum weight of the applicable configuration, and shall act parallel to the ground. In addition,

- **The vehicle shall be in the three-point attitude, with the resultant of the vertical reactions at the wheels equal to the maximum flight gross weight (atmospheric).**
- **The side component of the tow load at the main gear shall be reacted by a side force at the static ground line at the gear to which the load is applied.**
- **For tow loads applied to the nose or auxiliary gear where the configuration or type of swiveling provided prevents application of the loads in a given direction, the specified load which will not result in a side load on the wheel(s) shall be applied at the maximum attainable angle.**
- **Reaction loads in addition to vehicle inertia shall be provided when necessary for overall equilibrium.**
- **Additional loads which may be necessary for equilibrium shall be considered separately.**

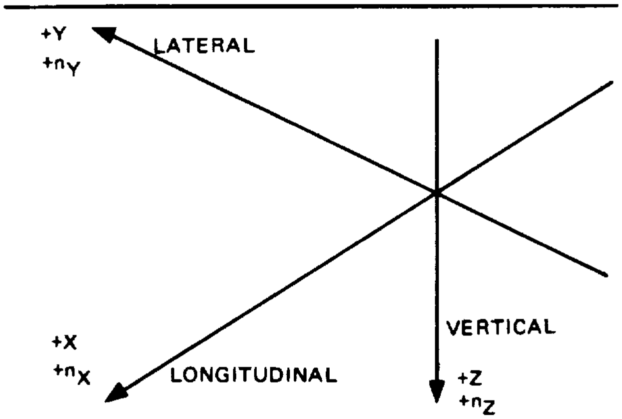

FIGURE 5-1 BODY AXES

TABLE 5-3 **TRANSPORTATION LIMIT-LOAD FACTORS** *

MODE	LONGITUDINAL (g)	LATERAL (g)	VERTICAL (g)
Marine	±0.5	±2.5	+2.5
Air	±3.0	±1.5	±3.0
Ground			
Truck	±3.5	±2.0	+6.0
Rail (humping shocks)	±6.0 to ±30.0	±2.0 to ±5.0	+4.0 to +15.0
Rail (rolling)	±0.25 to ±3.0	±0.25 to ±0.75	+0.2 to +3.0
Slow-moving dolly	±1.0	±0.75	+2.0

*For crash factors, see Section 5.2.12.3

- If a tow point is at or near a main-gear unit, a force acting at the axle of the wheel nearest the tow point in a direction opposite to the component of the tow load parallel to the plane of symmetry, equal in magnitude to this component or the vertical reaction at a main gear, whichever is lesser, shall be combined with inertial loads necessary for equilibrium.

- If a tow point is at the plane of symmetry, a force acting at the axle of the auxiliary or nose wheel in a direction opposite the direction of the tow load, equal in magnitude to this tow load or the vertical reaction at the auxiliary wheel, whichever is lesser, shall be combined with inertial loads necessary for equilibrium.

5.2.4.1.3 JACKING

Limit jacking loads shall be based on the maximum flight gross weight of the vehicle. The vertical load shall act singly and in combination with the longitudinal load, the lateral load, and both longitudinal and lateral loads. The horizontal loads at the jack points shall be reacted by inertial forces so as to cause no change in the vertical

TABLE 5-4 **TOWING CONDITIONS**

TOW POINT	TOWING LOAD: MAGNITUDE*	TOWING LOAD: DIRECTION OF LOAD APPLICATION
At or near each main gear	0.75 T per main gear unit	Positive, longitudinal
		Positive, at 30 deg to longitudinal
		Negative longitudinal
		Negative, at 30 deg longitudinal
At the nose gear	1.0 T	Positive, longitudinal
		Negative, longitudinal

*Value of T can be obtained from figure 5-2.

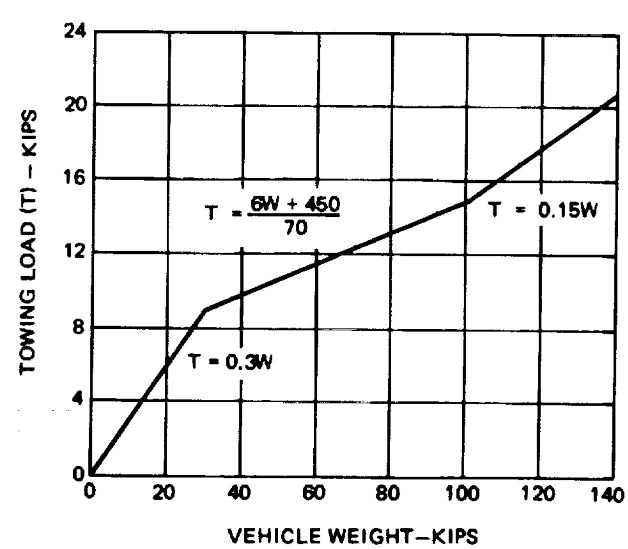

FIGURE 5-2 TOWING LOAD

loads at the jack points. Load factors of 2.0 g shall be applied in the vertical direction and load factors of 0.5 g shall be applied in any horizontal direction.

5.2.4.1.4 HOISTING
Limit-load factors for hoisting vehicle components shall be 2.0 g for land operations and 2.67 g for shipboard operations, applied upward in any direction within 20 deg of the vertical direction. The vehicle weight shall be the maximum landing gross weight.

5.2.4.1.5 MATING AND ERECTING
Limit-load factors for vertical mating and erecting of vehicle components shall be 2.0 g applied upward in the vertical direction and 0.5 g in any horizontal direction. The vehicle shall be considered to be within the attitude envelope established for the erecting and mating operation. The vehicle weight shall be identical to the basic landing gross weight (atmospheric), except that no allowance for personnel shall be included.

5.2.4.1.6 MOORING
The vehicle secured in the static horizontal or vertical attitude, and with control surfaces locked, shall be able to withstand ground winds (Sec. 6.2).

5.2.4.2 MASS PROPERTIES
Values of the design weights, centers of gravity, and mass moments of inertia to be used for all transportation and ground handling conditions shall include the flight article mass properties being handled and transported, and temporary installations (e.g., temporary pressurizing gases) and all supports which are used during transportation and handling but are not part of the flight article.

5.2.5 PRELAUNCH

5.2.5.1 LOADS AND PRESSURES

5.2.5.1.1 WINDS AND GUSTS
Static and dynamic loads resulting from winds and gusts (and resultant vortex shedding) during prelaunch shall be accounted for, including the effects of at least the following: the forward profile shape of the vehicle (e.g., vehicle nose); vehicle mass, stiffness, propellant loadings, and tank-pressurization conditions; protuberances and surface roughness; and proximity and shape of umbilical masts and other large structures. The resultant elastic-vehicle static and dynamic loads shall be obtained by suitable combination of the turbulence loads and steady loads, together with the periodic vortex-shedding loads calculated from the peak-wind profile. Tank-pressurization conditions shall account for the venting-system characteristics, including valve tolerances and settings for design ullage and vent pressure.

For recommended practices, see NASA SP-8008.

If a structural tie-off or damper to a launch-support structure is used to assist in withstanding wind loads imposed on the vehicle, the loads at the vehicle attachments shall be included in determination of the total vehicle loads.

5.2.5.1.2 UMBILICAL
Loads imposed on the vehicle by the umbilical shall be accounted for and shall include the effects of umbilical configuration, method of attachment, method of disconnect, feed-line pressures, and wind loads.

5.2.5.1.3 GROUND-TEST FIRING
The following loads imposed on the vehicles during ground-test firing of engines shall be accounted for: (1) static and dynamic loads resulting from ground winds and gusts, as identified in Section 5.2.5.1.1; and (2) static and dynamic loads due to thrust buildup and decay, including malfunction loads resulting from any number or combination of engines hard-over or out.

5.2.5.2 HEAT TRANSFER
Heat transfer resulting from at least the following shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure:

- Cryogens, including the effects of thermal cycling due to the introduction and removal of cryogens
- Environmental control system, including the effects of cooling-air pressure, temperature, and humidity
- Engine test firing, including the effects of test stand and ground plane
- Atmospheric temperature
- Solar radiation.

Refer to Section 5.1.2 for more detailed heat-transfer criteria.

5.2.5.3 MASS PROPERTIES
Values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the prelaunch conditions shall include: (1) the booster and

orbiter, mated and unmated; (2) level of propellant; (3) vehicle attitudes; (4) fueling sequences; (5) defueling sequences; (6) payload configuration; and (7) structural deflections.

5.2.6 LAUNCH

5.2.6.1 LOADS AND PRESSURES

5.2.6.1.1 WINDS AND GUSTS

Static and dynamic loads from winds and gusts (and resultant vortex shedding) during launch, as identified in Section 5.2.5.1.1, shall be accounted for.

Wind directions not parallel to the plane of vehicle symmetry, vortex shedding, and interference may cause large asymmetrical loads on the vehicle.

5.2.6.1.2 ENGINE FIRING

The following loads imposed on the vehicles as a result of booster-engine firing shall be accounted for:

- **Air loads induced by engine exhaust.**
- **Acoustic loads, including the effects of launcher and ground plane.**
- **Thrust-buildup loads, including engine start-time deviations.**
- **Thrust-vector misalignment loads. The bounds of the total thrust-vector misalignment shall be established considering all engines and using statistical methods.** (The misalignment loads should be evaluated even though the total thrust vector is normally programmed to pass through the center of gravity of the booster-orbiter combination for the launch-release condition.)
- **Loads resulting from engine hard-over or out after release. Loads for the engine hard-over or out condition shall be based on at least one engine hard-over or out, and on not more than the number which will cause vehicle-control instability.**

  The analysis of the engine hard-over or out condition should be in accordance with the procedure of Section 5.2.12.1. If abort specifications include engine conditions that result in vehicle instability, the analysis should be in accordance with the procedures of Sections 5.2.12.1 and 5.2.12.2.

  The same loads shall be considered for engine hard-over prior to release as for ground-test firing in the prelaunch phase.

- **Rebound loads from emergency engine shutdown prior to release, including thrust-decay characteristics in addition to all normal launch loads except for vehicle-release loads.**

For recommended practices, refer to NASA SP-8030.

5.2.6.1.3 VEHICLE RELEASE

Vehicle-release loads, including the effects of the release mechanisms on the vehicle's dynamic response, shall be accounted for.

5.2.6.2 HEAT TRANSFER

Heat transfer resulting from at least the following shall be accounted for in determination of temperatures and thermal stresses in critical areas of the structure: cryogens; environmental control system, including the effects of cooling-medium pressure, temperature, and humidity; engine firing, including the effects of launcher and ground plane; and atmospheric temperature.

5.2.6.3 MASS PROPERTIES

The values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the launch conditions shall include all nominal payloads and propellants with a 3σ tolerance and all off-load propellant and/or payload conditions with a 3σ tolerance.

5.2.7 ASCENT

5.2.7.1 LOADS AND PRESSURES

The determination of ascent loads and pressures shall include consideration of the following: (1) trajectory conditions of Section 5.2.7.4; (2) angles of attack, yaw, and roll within the flight-operational envelope; (3) effects of inflight winds, wind shears, and gusts; (4) effects of engine firing; (5) effects of staging; (6) influence of interference phenomena such as a piggyback stage, protuberances, and control surfaces; (7) effects of separated flow regions and of jet-plume interference on the flow fields; (8) effects of mass addition to or removal from the flow fields; (9) effects of shock impingement and interaction; (10) influences of vent locations and sizes; and (11) effects of vehicle flexibility on loading distributions.

Experimental data shall be utilized when empirical data suitable to the configuration and expected flight conditions are not available, when the design angle of attack or yaw induces nonlinear aerodynamic behavior, when large flow separations are expected to occur, and when large protuberances or severe wake generators exist on the

configuration. Experimental data shall also be utilized for the transonic-speed regime.

5.2.7.1.1 WINDS, GUSTS, AND TRAJECTORIES

The wind and gust data specified in Section 6.2 shall be used for determination of structural loads during the ascent phase. The design trajectories for ascent flight shall include dispersions in the conditions that significantly affect structural loads and temperatures. (See Secs. 5.1.2.1 and 5.2.7.1.)

5.2.7.1.2 ENGINE FIRING

Booster and orbiter engine-thrust magnitudes, engine-firing sequence, thrust transients, thrust-vector directional variations, and loads resulting from the engines-out condition shall be accounted for. The same conditions shall be included for the booster engine hard-over or out condition as for firing at launch.

The dynamic inputs for thrust excitation should be derived from experimental data obtained from the engine(s) under consideration, from similar engines, or from a logical extrapolation of related experimental data. For recommended practices, see NASA SP-8030.

5.2.7.1.3 STAGING

The following additional sources of loads imposed on the vehicles during staging shall be accounted for: separation or actuation devices, fluid slosh, exhaust-plume impingement, control system, and vehicle-separation dynamics.

Analyses should employ multidegree-of-freedom models incorporating coupled vibration modes of the continuing vehicle and of the jettisoned segments.

For recommended practices, refer to NASA SP-8022.

5.2.7.2 HEAT TRANSFER

Heat transfer from at least the following sources shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure: cryogens; engines; and external flow field, including shock and engine-plume impingement areas.

For more detailed heat-transfer criteria, refer to Section 5.1.2.

5.2.7.3 MASS PROPERTIES

Values of the design weights, centers of gravity, and mass moments and products of inertia to be used for the ascent conditions shall include the amounts of fuel remaining at each instant of time for all nominal payloads and propellants with a 3σ tolerance, and for all off-load propellant and/or payload conditions with a 3σ tolerance.

5.2.7.4 DESIGN TRAJECTORIES

The design trajectories for ascent flight shall include the dispersions in those parameters that have a significant effect on structural loads and temperatures.

In establishing the design trajectories for structural loads and thermal analyses, the effects of uncertainties in at least the following parameters shall be accounted for: aerodynamic characteristics, guidance system characteristics, thrust and thrust-misalignment tolerances, mass-property tolerances, and atmospheric density and wind dispersions.

In evaluation of loads, at least the following trajectory conditions shall be included:

- Point(s) of maximum dynamic pressure
- Point(s) at which the product of the dynamic pressure and angle of attack is a maximum
- Point(s) of maximum longitudinal acceleration and deceleration
- Point(s) where centers of pressure are at extreme locations
- Point(s) of maximum heating rate
- Point(s) of maximum temperature
- Point(s) of maximum and minimum inertial loading
- Point(s) of maximum differential pressure across the structure
- Several points in the transonic-speed regime, including the point at which the free-stream Mach number is one
- At least one subsonic point below the transonic regime
- Point(s) of pitch-yaw coupling for rolling vehicles
- Point(s) of maximum and minimum pressure on compression and expansion surfaces
- Point(s) of maximum fluctuating pressure.

In evaluation of heat transfer from the external flow field, either the aerodynamic-heating indicator or summation of flat-plate convective-heating rates is recommended for preliminary analysis of the effects of the

parameter dispersions, but critical heating areas should be examined in more detail before final design is completed. (See NASA SP-8029.)

5.2.8 SPACE

5.2.8.1 LOADS AND PRESSURES

5.2.8.1.1 ORBIT TRANSFER AND DEORBIT

The static and dynamic loads experienced by the vehicle during orbit transfer and deorbit operations shall be accounted for.

5.2.8.1.2 DOCKING AND UNDOCKING

Loads imposed on the orbiter during docking and undocking shall be accounted for, including the effects of relative velocities and misalignments, liquid slosh produced by docking impact and undocking dynamics, latching and unlatching forces and torques, and engine thrust during undocking and maneuvers. The following configuration combinations shall be evaluated:

- **Orbiter – Orbiter**
- **Orbiter – Space station or base**
- **Orbiter – Space station or base – Other orbiter(s).**

The docking loads shall be evaluated using the following relative velocities and misalignments, although lower values may be used if substantiated by docking-simulator studies:

Parameter	Impact values
Closing velocity, ft/sec (parallel to docking port)	0.4
Lateral translation, ft/sec (in any direction perpendicular to closing velocity vector)	0.15
Angular velocity, deg/sec (in any plane)	0.1
Linear misalignment, in.	±6.0
Angular misalignment, (including roll), deg	±3.0

The velocities and misalignments should be considered in combinations limited by the following:

$$\frac{(V_L - V_{Lm})^2}{(\Delta V_L)^2} + \frac{V_R^2}{(\Delta V_R)^2} + \frac{D_R^2}{(\Delta D_R)^2} = 1$$

$$\frac{\omega_x^2 + \omega_y^2 + \omega_z^2}{(\Delta\omega)^2} + \frac{\theta_x^2 + \theta_y^2 + \theta_z^2}{(\Delta\theta)^2} = 1$$

where

V_L and V_R are the closing and lateral translation velocities

D_R is the linear misalignment

V_{Lm} is the mean closing velocity

ω_x, ω_y, and ω_z are the angular velocities about the respective axes

θ_x, θ_y, and θ_z are the angular misalignments about the same axes

and

Δ is the increment to be considered above and below the mean value or zero.

5.2.8.1.3 CARGO TRANSFER

All static and dynamic loads due to opening and latching forces, movement of cargo, control-system interaction, and the absence of aerodynamic damping and gravity in orbit shall be accounted for.

5.2.8.2 HEAT TRANSFER

Heat transfer resulting from at least the following shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure: (1) cryogens; (2) power supplies and other heat-producing equipment in orbiter(s) and space station or base; (3) engines, including attitude-control and maneuvering engines; (4) solar radiation; and (5) albedo of earth, moon, and objects in interlunar space.

For more detailed heat-transfer criteria, refer to Section 5.1.2.

5.2.8.3 MASS PROPERTIES

Values of the design weights, centers of gravity, and mass moments and products of inertia to be used for all space-flight configurations shall include all nominal payloads and propellants with a 3σ tolerance; all off-load propellant and/or payload conditions with a 3σ tolerance; and mass properties of the space station, space base, or other orbiter(s) to which the orbiter is docked.

5.2.9 ENTRY

5.2.9.1 LOADS AND PRESSURES

All static and dynamic loads and pressures acting on the vehicle during entry shall be accounted for. The determination of air loads shall account for the effects of maneuvers, winds and gusts, vehicle attitude, and shock impingement and interaction associated with at least protuberances, canopies, fins, nose cap, deflected control surfaces, engine plumes, and boundary layer. Auxiliary surface deployment, boundary-layer conditions, viscous-induced pressures, body flexibility, and vorticity resulting from leading edges, intersecting flow fields, and abrupt geometry changes shall also be accounted for. Experimental data shall be utilized when validated theoretical analyses applicable to the configuration and flight conditions are not available and when large flow separations, protuberances, or wake generators exist on the configuration.

5.2.9.2 HEAT TRANSFER

Heat transfer from at least engines and the external flow field, including shock and engine-plume impingement areas, shall be included in evaluation of temperatures and thermal stresses in critical areas of the structure and in evaluation of the effectiveness of thermal protection systems.

For more detailed heat-transfer criteria, refer to Section 5.1.2.

5.2.9.3 MASS PROPERTIES

Values of the design weight, centers of gravity, and mass moments and products of inertia to be used for the entry flight conditions shall include the maximum entry design gross weight and all lesser gross weights down to and including the minimum entry gross weight at which critical conditions can be achieved.

The analysis at each gross weight should include all reasonable distributions of payload and disposable items. These distributions should be presented in the form of plots showing the variations in center of gravity in the three planes of the body's axis system.

Minimum Entry Gross Weight. Values of the minimum entry gross weight shall include an allowance for minimum crew, minimum propellant remaining in the primary propulsion system or other expendables, and for a full load of cruise engine fuel and oil. It shall be assumed that no propellant remains for attitude control and that there is no payload or other useful load item.

Maximum Entry Design Gross Weight. Values of the maximum entry design gross weight shall include an allowance for full crew, full load of cruise engine fuel and oil, maximum payload, and any propellant remaining in the primary propulsion system or other expendables. It shall be assumed that all propellant remains for attitude control and that there are other useful load items.

5.2.9.4 DESIGN TRAJECTORIES

Entry flight trajectories for use in determination of structural loads and aerodynamic heating shall include the dispersions in parameters in the design entry corridor which have a significant effect on loads and temperatures.

5.2.9.4.1 DESIGN ENTRY CORRIDOR

The design entry corridor, defined in terms of velocity versus altitude within the design atmosphere, shall be represented by an envelope of operational trajectories that satisfy the mission requirements.

Altitude margins, relative to the nominal trajectory values, should be derived from simulator studies involving tolerances and uncertainties in those systems and environmental parameters that have a significant effect on loads and temperature conditions. These trajectories should include the ideal energy-management maneuver required during the initial entry period to establish the desired glide conditions. A corridor, as illustrated in figure 5-3, should be developed for NASA approval.

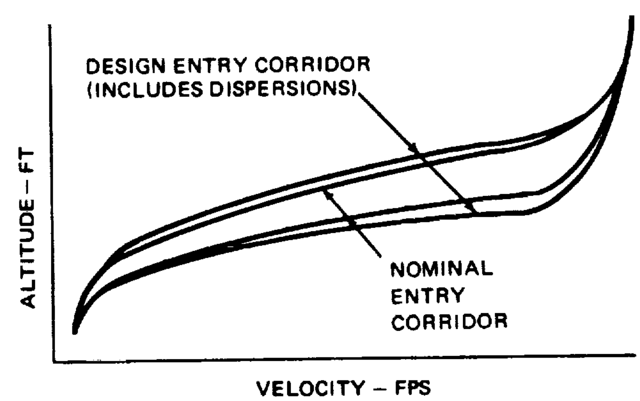

FIGURE 5-3 DESIGN ENTRY CORRIDOR

An acceptable approach to development of the corridor follows:

1. Define the nominal entry corridor for ideal conditions (no dispersions), using the ideal entry trajectories from the baseline orbit and from the critical orbits within the range of inclinations specified for design. The top (highest altitude) boundary is defined by an ideal minimum W/SC_L trajectory based on maximum C_L and minimum gross weight. The bottom boundary is defined by an ideal maximum W/SC_L trajectory for a maximum entry gross weight and a bank-angle history required for the specified cross range.

2. Establish the effect on trajectory altitude of incremental dispersions in each parameter that has a significant influence on loads and heating. As a minimum, incremental dispersions in the following parameters should be considered:

   A. Angle-of-attack dispersions due to tolerances and uncertainties in the pilot's instrumentation system, the autopilot system, the guidance and control system, and the aerodynamic data.

   B. Angle-of-roll dispersions due to the tolerances and uncertainties listed in (A).

   C. Flight-path-angle and velocity dispersions at entry due to tolerances in the effective retro-rocket impulse resulting from dispersions in vehicle attitude, retrorocket thrust, burn time, etc.

   D. Aerodynamic-coefficient dispersions.

   E. Atmospheric-property dispersions (including winds and gusts).

   F. Uncertainty of orbit at retro.

3. The boundaries of the nominal entry corridor should be expanded to account for the incremental dispersions, and should be established based on statistical combination of the dispersions with consideration given to their coexistence at the specific time.

5.2.9.4.2 DESIGN ENTRY TRAJECTORIES

Design entry trajectories shall be based on the ideal entry trajectories in the design atmosphere with transient excursions out to the boundaries of the design entry corridor. A sufficient number of design entry trajectories shall be established to ensure that all critical structural heating and load conditions that occur in the design entry corridor have been adequately covered.

5.2.9.4.3 TRANSIENT MANEUVER ENVELOPE

A transient maneuver envelope for entry flight shall be established based on the aerodynamic capability of the vehicle, the aerodynamic environment, and the type of maneuver likely to be performed in each velocity range. The critical combination of loads, temperatures, and other conditions represented in the transient maneuver envelope shall be accounted for.

Selection of the critical conditions should be based on analysis of coexisting structural temperatures, loads, pressures, and other parameters. The analysis should account for the time-dependency and phasing of these parameters.

A maneuver envelope (V-n diagram) for the orbiter and the booster is illustrated in figure 5-4. Booster load-factor requirements may be more severe than orbiter requirements because they depend strongly on staging altitude, velocity, and flight-path angle. The values for the maximum normal load factors should include the particular vehicle entry characteristics, pilot-control inputs, and the flight-control system characteristics for the initial entry and glide phases of flight.

During the initial entry period, prior to acquisition of the glide conditions, the precise roll angle and angle of attack are modulated to avoid excessive structural loads and induced environments, and to prevent skipout. The load factors should be established for conditions at the boundaries of the design entry corridor and should include the load factor for the ideal maneuver at the boundary, plus an increment to provide capability to maneuver away from the boundary.

The transient maneuver envelope for the glide portion of the entry should be based on conditions at the

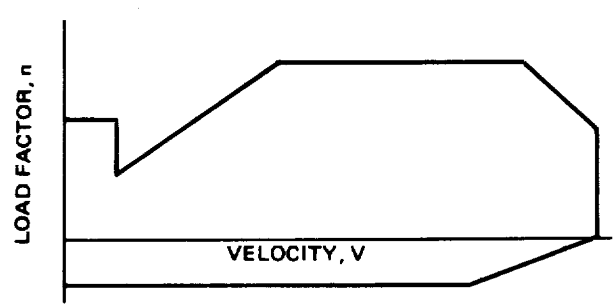

FIGURE 5-4 ORBITER OR BOOSTER MANEUVER ENVELOPE

boundaries of the design entry corridor. The load factor for each velocity range should be based on the attitude required for glide at conditions that define the design boundary, plus an increment to correct for deviations from the flight plan or to modify the flight plan.

Prior to completion of simulator studies conducted to develop the actual maneuver load-factor requirements, transient maneuver load-factor requirements may be defined by using the static loads based on the vehicle attitudes and conditions on the nominal entry boundary and increasing them by 10 percent.

5.2.10 ATMOSPHERIC FLIGHT

The loads and environments experienced by the booster or orbiter structure in atmospheric flight and represented in the V-n flight envelopes shall be accounted for. Conditions imposed on the structure during atmospheric flight which are more severe than those imposed in any other flight phase shall be identified. The residual effects of loads and environments encountered in space and entry flight, including load redistribution from thermally induced deformations, reduced material allowables, and changes in vibration modes and frequencies, shall be accounted for.

5.2.10.1 LOADS AND PRESSURES

Loads shall be evaluated for the conditions identified for the entry phase and for at least the following speeds: level flight maximum speed, V_H; limit speed, V_L; stalling speeds, V_S, V_{SL}, and V_{SPA}; and the speed for maximum gust, V_G.

The speeds used to determine loads for atmospheric flight, not including takeoff and landing approach, shall be defined for the altitude at which the limit speed, V_L, in EAS is maximum, the altitude at which the Mach number is maximum, sea level, and for any intermediate altitude at which critical loads occur. Sea level speeds shall be used for landing approach and takeoff loads.

Loads and pressures for both symmetrical and unsymmetrical flight maneuvers shall be accounted for.

5.2.10.1.1 MANEUVERS

5.2.10.1.1.1 Symmetrical Flight

For a balanced maneuver, the vehicle shall be considered to be in the basic and the high-drag configurations at all points on and within the maneuvering envelope illustrated in figure 5-5. The pitching velocity shall be the finite pitching velocity associated with the load factor developed. It shall be assumed that the elevator is deflected at a very slow rate so that the pitching acceleration is zero. In addition, at the limits of the envelope shown in figure 5-5, the pitching acceleration shall be the maximum attainable with the control system

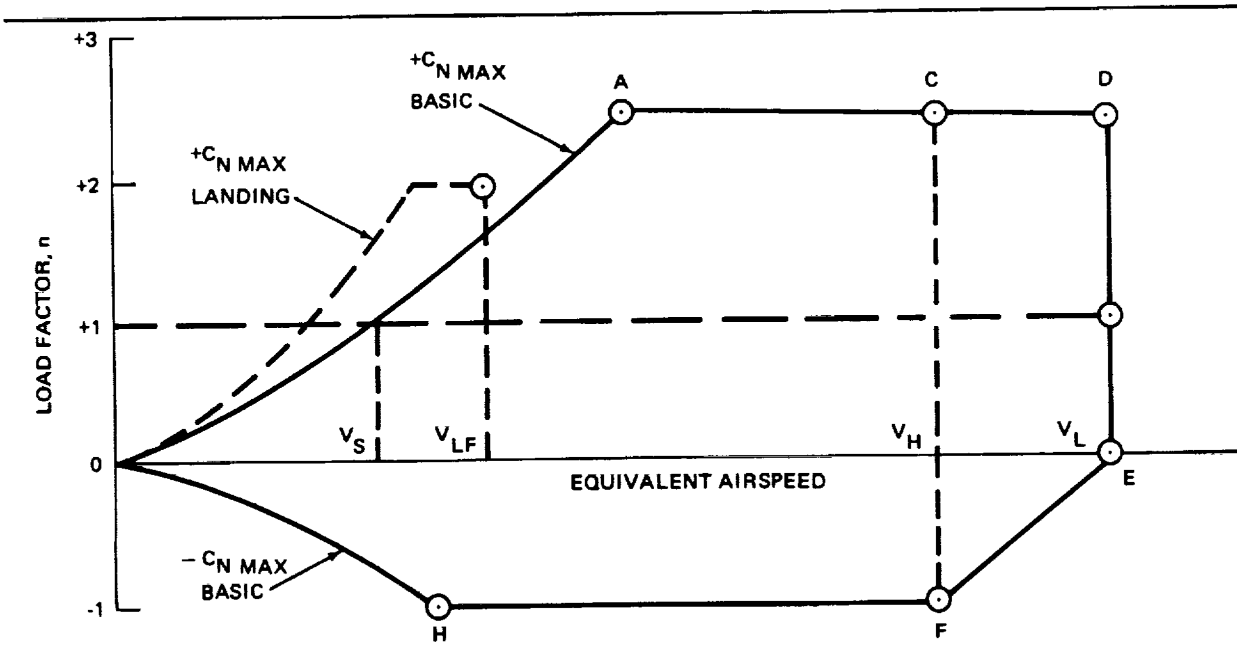

FIGURE 5-5 SYMMETRICAL MANEUVER ENVELOPE

and in a direction that reduces the load factor. Balance shall be established between aerodynamic and inertial forces.

Except where vehicle design or the maximum (static) lift coefficient makes it impossible to exceed a lower value, the envelope shall be defined as follows:

- The positive limit maneuvering load factor for any speed up to V_L may not be less than 2.5.
- The negative limit maneuvering load factor may not be less than 1.0 at speeds up to V_H and must vary linearly with speed from the value at V_H to zero at V_L.
- For a symmetrical maneuver with pitch, the vehicle shall be considered to be in the basic and the high-drag configurations, and based on a rational pitching-control-motion-versus-time profile.

The vehicle initially shall be in steady unaccelerated flight at the airspeed specified for the maneuver and trimmed for zero control forces at that airspeed. The airspeed shall be constant until the specified load factor has been attained. The load factors to be obtained shall be all values on and within the envelope illustrated in figure 5-5. The load factor at each airspeed shall be obtained as indicated below for all center-of-gravity positions:

- By a control movement resulting in a triangular displacement-time curve, as illustrated by the solid straight lines of figure 5-6(a), provided that the specified load factor can be attained by such control movement; otherwise, by the ramp-style control movement illustrated by the dashed straight lines of this figure. The time t_1 is specified as 0.4 sec for the ramp-type control movement; the time t_2, while the control surface is held at the stops, shall be the minimum time required to attain the specified load factor.
- By a control movement resulting in a ramp-type displacement-time curve, as illustrated by the solid straight lines of figure 5-6(b). The time t_1 is specified as 0.4 sec. The time t_3 and the control displacement δ shall be sufficient to attain the specified load factor in time $2t_1$ plus t_3.
- In addition, for maximum aft center-of-gravity position, the load factor shall be obtained by a control movement resulting in a ramp-type displacement-time curve, as illustrated by the solid straight lines of figure 5-6(c). The time t_1 is specified as 0.4 sec. The time t_4 and the control displacement δ and minus $\delta/2$ shall be sufficient to attain the specified load factor coincidentally with the attainment of minus $\delta/2$.

For a symmetrical maneuver with the vehicle in the landing-approach configuration, the vehicle shall be at the limit speed, V_{LF}, and the load factors shall be all values from 0 to 2.0. Balanced and symmetrical maneuvers with pitch conditions shall apply. The longitudinal control displacement shall be the same as indicated for the basic and high-drag configurations.

5.2.10.1.1.2 Unsymmetrical Flight

For rolling pull-out, the vehicle shall be considered to be in the basic and high-drag configurations. The airspeeds shall be all airspeeds up to V_L and the directional control shall be held in a fixed position for trim in wings-level flight without rudder-control force at the speed required and displaced as necessary to prevent sideslip. Cockpit lateral control shall be displaced to the maximum position, and the control force shall be applied for not more than 0.3 sec. The control force shall be maintained

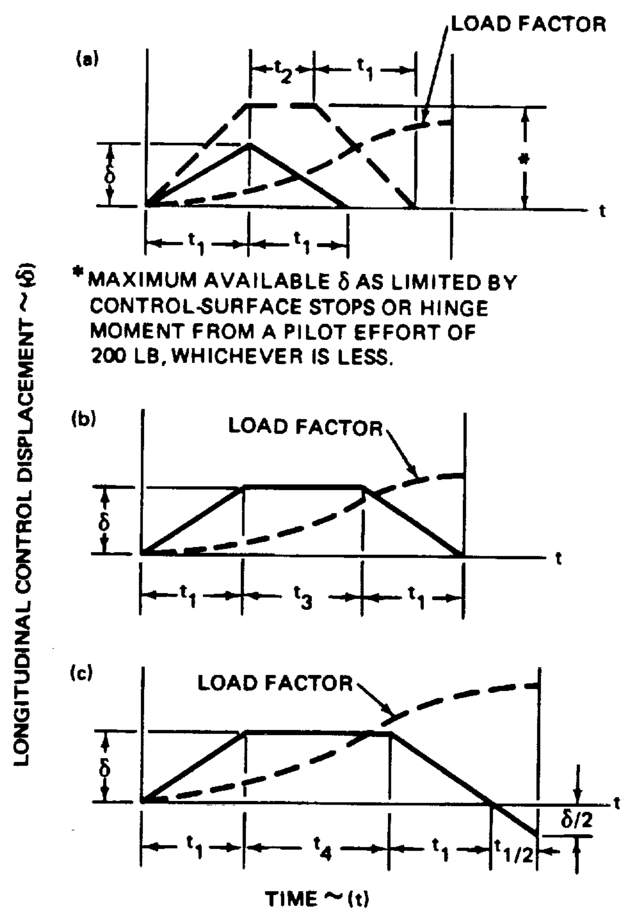

FIGURE 5-6 LONGITUDINAL CONTROL DISPLACEMENT–TIME DIAGRAM

until the required change in angle of bank is attained, except that, if a roll rate greater than a specified value would result, the control position may be lessened after attaining the maximum rolling acceleration to that position resulting in the specified roll rate. The maneuver shall be checked by application of the maximum displacement in not more than 0.3 sec.

For accelerated roll, the vehicle shall be considered to be in the basic and high-drag configurations. The airspeed shall be all airspeeds up to V_L and the initial load factor shall be all positive values between 1.0 and 0.8 of the maximum values shown in the maneuvering envelope illustrated in figure 5-5. The vehicle shall be initially in a steady, constant-altitude turn at an angle of bank to attain the load factor at the specified airspeed. The vehicle shall roll out of the turn through an angle of bank equal to twice the initial angle. Constant airspeed and constant cockpit longitudinal-control position shall be maintained.

For roll in takeoff and landing configurations, the airspeed shall be V_{LF} in the landing approach configuration. The load factor shall be unity. The lateral control shall be displaced in accordance with the rolling pull-out, and the roll need not be carried beyond a 60-deg angle of bank.

For sideslips and yawing, lateral-control displacement shall be used to maintain the wings in a level attitude, except that for high-speed rudder-kick conditions, an angle of bank of not more than 5 deg shall be maintained.

The minimum speeds shall be considered the minimum speeds at which the angle of bank can be maintained. For all of the following conditions except that of a one-engine-out operation, normal load factor shall be unity.

1. Unsymmetrical thrust with zero sideslip. The most critical engine shall not be operating and the vehicle shall be in the minimum drag configuration. All other engines shall deliver takeoff thrust or power. The vehicles shall be in the takeoff and landing configurations at V_{LF} and in the basic and high-drag configurations at maximum flight speed.

2. Engine failure. The vehicle shall be in the basic configuration. The airspeeds shall be all speeds from the approved one-engine-out minimum takeoff speed to V_H. The critical engine shall suddenly fail. If reverse thrust is possible because of automatic features, the failed engine shall deliver reverse thrust. All other engines shall deliver normal-rated power or thrust, except that takeoff power or thrust is applicable at speeds up to 2 V_{SL}. Automatic decoupling or thrust-controlling devices shall be operating and alternately not operating. With these devices operating, limit strength is required. The directional control shall:

   A. Be held in the neutral position until maximum sideslip is attained.

   B. Be moved to the position attainable with maximum rudder deflection.

3. Steady sideslip. The vehicle shall be in the basic and high-drag configurations. The airspeed shall be all speeds up to V_L. Rudder control shall be applied slowly to a maximum position.

4. Low-speed rudder kick. The vehicle shall be in the takeoff and landing configurations at speeds up to V_{LF}. The cockpit directional control shall be displaced in not more than 0.3 sec to the maximum displacement attainable, as limited by stops or maximum output of the power-control system or specified directional control force. The control displacement or force shall be maintained until the maximum overswing angle of sideslip is attained and the vehicle reaches a steady sideslip. Recovery shall be made by reducing the directional-control displacement to zero in not more than 0.3 sec.

5. High-speed rudder kick. The vehicle shall be in the basic and high-drag configurations at speeds up to V_H. The cockpit directional control force shall be applied in not more than 0.2 sec. Recovery shall be made by reducing the directional-control displacement to zero in not more than 0.3 sec.

6. One-engine-out operation. Sudden stopping of an engine at all speeds above the approved one-engine-out minimum takeoff speed up to V_H shall not result in unacceptable vehicle motions or vibrations within these specified speed ranges. The limit loads on the vehicle shall not be exceeded in a symmetrical pull-out to a load factor of 2.0, with each engine, one at a time, inoperative and all other engines delivering normal-rated power or thrust.

These criteria should not be construed to supersede or obviate applicable flying qualities or power-plant-installation requirements for one-engine-out operation, and should be reexamined after simulation studies are made.

5.2.10.1.2 GUSTS

Loads for at least the following gust conditions shall be accounted for: (1) symmetrical vertical gusts in level flight, (2) lateral gusts, and (3) continuous turbulence gusts.

5.2.10.1.2.1 Symmetrical Vertical

For symmetrical vertical gusts in level flight, consider the vehicle to be in the basic flight and landing configurations. The symmetrical gust envelope, illustrated in figure 5-7, shall be prepared in the following manner:

1. Velocities shall be as specified below except that at altitudes greater than 20 000 ft, the specified equivalent gust velocity, U_{de} shall be multiplied by the factors $\sqrt{\sigma_h}/\sqrt{\sigma_r}$, where σ_h is density at altitude and σ_r is density at 20 000-ft altitude.

Points	Configuration	Airspeed	Gust Velocity (EAS)
B′ and G′	Basic	V_G	U_{de} = 66 fps
C′ and F′	Basic	V_H	U_{de} = 50 fps
D′ and E′	Basic	V_L	U_{de} = 25 fps
I′ and J′	Landing	V_{LF}	U_{de} = 50 fps

If the landing configuration includes the use of flaps, the vehicle shall be assumed to encounter a head-on gust of 25 fps (EAS) at V_{LF}.

2. To calculate the gust load factor, the following assumptions shall be made:

The shape of the gust is

$$U = \frac{U_{de}}{2}\left(1 - \cos\frac{2\pi s}{25\bar{C}}\right)$$

where

U = gust velocity, fps

U_{de} = derived gust velocity, fps

s = distance penetrated into gust, ft

$\bar{C}$ = mean geometric chord of wing, ft

Gust load factors vary linearly between the specified conditions B′ through G′, as shown in the gust envelope in figure 5-7.

3. In the absence of a more rational analysis, the gust load factors shall be computed as follows:

$$n = 1 + \frac{K_g U_{de} V a}{498\,(W/S)}$$

where

$$K_g = \frac{0.88\,\mu_g}{5.3 + \mu_g} = \text{gust alleviation factor}$$

$$\mu_g = \frac{2(W/S)}{\rho\, a\, \bar{C}\, g}$$

W/S = wing loading, psf

ρ = density of air, slugs/ft^3

g = acceleration due to gravity, ft/sec^2

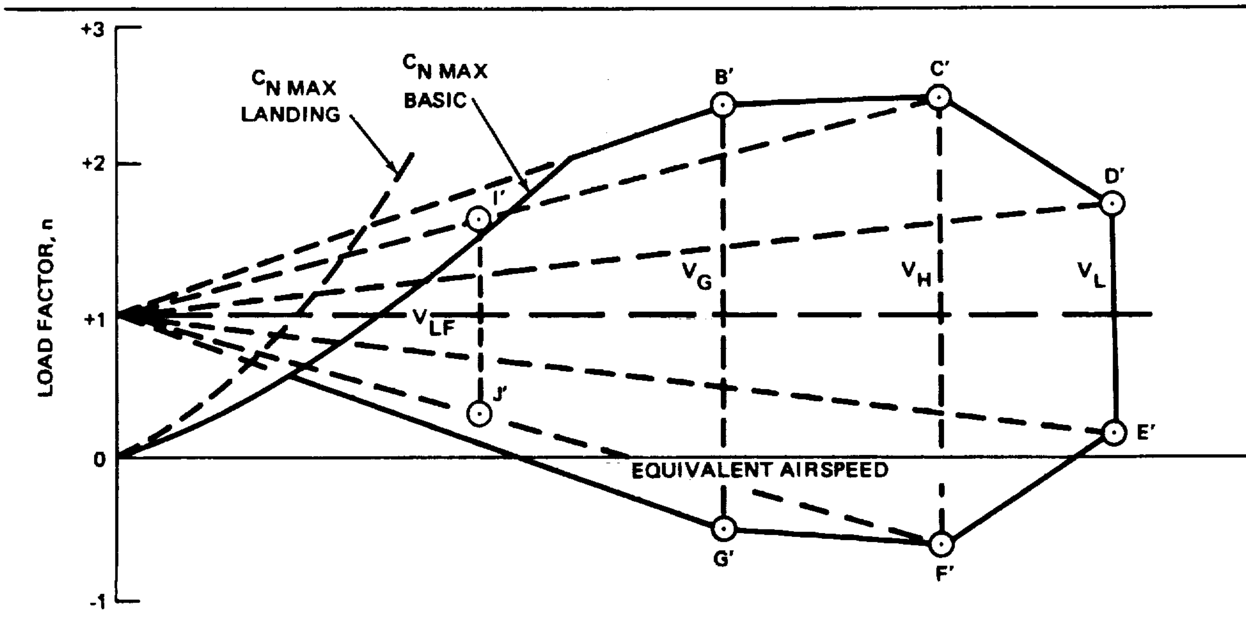

FIGURE 5-7 SYMMETRICAL GUST ENVELOPE

V = vehicle equivalent speed, knots

a = slope of the vehicle normal-force coefficient curve C_{N_A} per radian if the gust loads are applied to the wings and horizontal tail surfaces simultaneously by a rational method. The wing-lift-curve-slope C_L per radian may be used when the gust load is applied to the wings only and the horizontal tail gust loads are treated separately.

5.2.10.1.2.2 Lateral

For lateral gusts, consider that the vehicle shall encounter derived gusts normal to the plane of symmetry while in unaccelerated wings-level flight (1) with all engines operating, (2) with all engines not operating, and (3) in a wings-level steady sideslip with the most critical engine not operating. The derived gusts and vehicle airspeeds corresponding to conditions B′ through J′, as defined for symmetrical gusts, shall be investigated. The gust shape shall be as specified for symmetrical gusts. In the absence of a rational investigation of the vehicle response to a gust, the gust loading on the vertical tail surfaces shall be computed as follows:

$$L = \frac{K_g U_{de} VaS}{498}$$

where

L = vertical tail load, lb

S = area of vertical tail, ft^2

and all other symbols are as defined for symmetrical gusts.

5.2.10.1.2.3 Continuous Turbulence

For continuous turbulence gusts, the gust-loads spectra shall be as defined in NASA TM X-53957 to maintain a 1-percent or lower risk of exceeding limit loads during the expected hours of vehicle flight in each flight phase. The analysis shall include at least the dynamic response in the rigid-body modes of pitch and translation. The dynamic response due to elastic modes shall also be analyzed, as appropriate, including interaction with the control system.

5.2.10.1.3 MANEUVER AND GUST

Maneuver and gust envelopes shall be defined for at least the transition- and cruise-flight regimes, and for landing.

For transition flight, three envelopes are required, one each at maximum transition altitude, midtransition altitude, and minimum transition altitude. The maximum normal load factor shall be derived from simulator studies of the transition maneuver.

Prior to completion of these studies, the normal load factor of the standard transport airplane of 2.5 (fig. 5-5) may be used.

For cruise flight, three envelopes are required, one each at maximum cruise altitude, ideal cruise altitude, and at sea level. The maximum normal load factor shall be 2.5 unless the vehicle has design features that make it impossible to exceed a lower value.

For landing, two envelopes are required, one at sea level and one at 5000-ft altitude.

Enough points on the maneuver and gust envelopes shall be investigated to ensure that the maximum load for each part of the vehicle structure is obtained.

A conservative combined envelope may be used.

The design loads and loading distributions shall include the significant forces acting on the vehicle placed in equilibrium in a rational or conservative manner and the effect of pitching velocities in turns and pull-ups. The linear and angular inertial forces shall be in equilibrium with the externally applied aerodynamic forces and moments.

5.2.10.1.4 ENGINES

All engine-operating conditions from zero to maximum thrust and rpm with gyroscopic loads associated with maneuvers and gusts shall be accounted for.

A limit lateral load factor shall be used which is at least equal to the maximum load factor obtained in the yawing conditions, but not less than 1.33.

The 1.33-limit lateral factor may be assumed to be independent of other flight conditions.

A limit torque load imposed by an abrupt engine stoppage from malfunction (e.g., compressor jamming) or structural failure shall be accounted for.

5.2.10.1.5 DECELERATORS

Loads from the stowage and deployment of aerodynamic decelerators (e.g., rotors) shall be accounted for. An

analysis shall be performed accounting for the effects of deployment altitude, deployment rate, heating and heating rate, and dynamic loads. The analysis shall use the maximum dispersed velocity and altitude at initiation of recovery, and the weight, center of gravity, and tolerances at that time.

For recommended practices, refer to a forthcoming NASA special publication on deployable aerodynamic deceleration systems.

5.2.10.1.6 HORIZONTAL AND VERTICAL TAILS

The air loads on the horizontal tail shall be distributed symmetrically and unsymmetrically, in combination with the specified maneuver and gust conditions. In addition, the horizontal tail loads shall be distributed as follows: 100 percent of the maximum load intensity from the symmetrical flight conditions acting on one side of the plane of symmetry and 80 percent of this load intensity acting on the other side. The air loads on the vertical tail or tails resulting from unsymmetrical maneuvers and lateral gusts shall be determined.

5.2.10.1.7 PILOT-APPLIED LOADS

Pilot-applied loads (table 5-5) shall apply to manual, manual-backup, and manually reversible systems having conventional aircraft stick or wheel and rudder controls. Other systems shall be designed to a rationally determined set of control loads.

Dual Control Systems. For vehicles provided with dual control systems, 75 percent of the pilot-applied loads shall be applied simultaneously at both control stations.

Duplicate Control Systems. For vehicles provided with duplicate control systems, 100 percent of the pilot-applied loads shall be applied to each system, assuming the other system to be disconnected.

Powered Control Systems. For vehicles equipped with powered control systems, the power system shall be considered as both operative and inoperative. For redundant systems, a single system shall be considered inoperative.

Reactions. Forces reacting to the pilot-applied loads shall be provided by:

- Control-system stops only
- Control-system locks only
- Components specifically designed to react to pilot-applied loads
- Irreversible mechanism only, with the irreversible mechanism locked with the control surface in all possible positions
- Attachments of the longitudinal-control system to the control-surface horn only, with the cockpit longitudinal control in all possible positions
- Attachments of the lateral-control system to control-surface horn only, with the cockpit lateral control in all possible positions
- Attachment of the directional-control system to the control-surface horn only, with the cockpit directional control in all possible positions.

5.2.10.2 MASS PROPERTIES

The mass properties to be used for atmospheric flight conditions shall include gross weights at the following configurations and all lower weights down to and including the minimum flying gross weight at which critical loads are achieved:

- Minimum flying
- Basic flight (atmospheric)
- Maximum flight (atmospheric)
- Basic landing (atmospheric)
- Maximum ferry and training flight
- Ferry and training flight landing.

5.2.10.2.1 MINIMUM FLYING

The minimum flying gross weight shall include an allowance for:

- Minimum crew
- 5 percent of cruise-engine fuel (for flying qualities, flutter-and-divergence prevention, and vibration analyses, no fuel shall be assumed)
- Oil consistent with 5 percent fuel
- Hydraulic fluids
- Ballast.

No other useful load items shall be assumed.

TABLE 5-5 PILOT-APPLIED LOADS

AIRPLANE CONTROL	COCKPIT CONTROL	NUMBER OF FORCES	MAGNITUDE OF EACH FORCE (LB)	POINT OF APPLICATION	DIRECTION
Lateral	Stick	1	100	Top of stick grip	A lateral force perpendicular to a straight line joining the top of the stick grip and the pivot point
	Wheel	2	80	One force at any point on circumference of wheel, other force at diametrically opposite point	Each force tangent to wheel rim acting in opposite directions
		1	100	On circumference of wheel	Tangent to wheel rim in plane of wheel
Longitudinal	Stick	1	200	Top of stick grip	A longitudinal force perpendicular to a straight line joining the top of the stick grip and the pivot point
	Wheel	2	100	One force at any point on circumference of wheel, other force at diametrically opposite point	Each force in same direction perpendicular to the plane of the wheel
		1	100	Any point on circumference of wheel	Perpendicular to the plane of the wheel
Directional	Rudder pedal	1	300	Point of contact of foot with pedal	Parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean flying position
		2	300	Each force at point of contact of foot with each pedal	Each force in same direction parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean flying position
Brake	Brake pedal	1	300	Point of contact of foot with pedal	Parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean landing position

TABLE 5-5 **PILOT-APPLIED LOADS (CONCLUDED)**

<table>
<tr><th>AIRPLANE CONTROL</th><th>COCKPIT CONTROL</th><th>NUMBER OF FORCES</th><th>MAGNITUDE OF EACH FORCE (LB)</th><th>POINT OF APPLICATION</th><th>DIRECTION</th></tr>
<tr><td>Brake</td><td>Brake pedal</td><td>2</td><td>300</td><td>Each force at point of contact of foot with each pedal</td><td>Each force in same direction parallel to the projection on the airplane plane of symmetry of a line connecting the point of application and the pilot's hip joint, with the pilot's seat in its mean landing position</td></tr>
<tr><td rowspan="3">Miscellaneous; e.g., throttles, flap. tab, stabilizer, spoiler, alighting gear, arresting hook, and wing-folding operating controls</td><td>Crank, wheel, or lever operated by push or pull force</td><td>1</td><td>$\left(1 + \frac{R}{3}\right) 50$ but not less than 50 nor more than 150 [R = radius (in.)]</td><td>Circumference of wheel or grip of crank or lever</td><td>Any angle within 20 deg of plane of control</td></tr>
<tr><td rowspan="2">Small wheel or knob</td><td colspan="4">133 in.-lb if operated only by twisting</td></tr>
<tr><td colspan="4">100 lb if operated only by push or pull</td></tr>
</table>

5.2.10.2.2 BASIC FLIGHT (ATMOSPHERIC)

The basic flight gross weight (atmospheric) shall include an allowance for:

- **Full crew**
- **Full load of cruise-engine fuel and oil**
- **Maximum payload**
- **Full load of auxiliary power fuel and system fluids**
- **Any propellant remaining in the primary propulsion system or other expendables**
- **40 percent of the propellant remaining for attitude control.**

The basic flight weight is applicable to flight-loads computations, to flutter-and-divergence prevention, and to vibration analyses.

5.2.10.2.3 MAXIMUM FLIGHT (ATMOSPHERIC)

The maximum flight gross-weight (atmospheric) allowance shall be identical to the basic flight allowance except that the propellant remaining for attitude control shall be increased to 100 percent.

The maximum flight gross-weight allowance is applicable to taxiing, towing, ground handling, jacking, flutter-and-divergence prevention, and vibration analyses.

5.2.10.2.4 BASIC LANDING (ATMOSPHERIC)

The basic landing gross-weight (atmospheric) allowance shall be the basic flight allowance minus 50 percent of the cruise-engine fuel.

This weight allowance is applicable to orbiter landings subsequent to entry from orbit; booster return from boost operations; booster or orbiter return from an aborted mission; and taxiing and ground handling after landing.

5.2.10.2.5 MAXIMUM FERRY AND TRAINING FLIGHT

The maximum ferry and training flight gross weight shall include an allowance for:

- **Full crew**
- **Full load of cruise-engine fuel and oil (including auxiliary tanks)**

2

- Full load of auxiliary power-system fuel and system fluids
- Auxiliary propulsion-system modules and ballast, if any.

No weight reduction shall be permitted for fuel used during taxi, warmup, or climb-out.

The weight allowance for maximum ferry and training flight is applicable to taxiing and ground handling, takeoff, flight, flutter-and-divergence prevention, and vibration analyses.

5.2.10.2.6 FERRY AND TRAINING FLIGHT LANDING

The weight allowance for ferry and training flight landings shall be the maximum ferry and training-flight gross weight minus 50 percent of the cruise-engine fuel and oil.

5.2.11 LANDING AND HORIZONTAL TAKEOFF

All loads and environments imposed by landing and horizontal takeoff operations, including taxiing, braking, and takeoff run shall be accounted for. The residual effects of loads and environments in atmospheric, entry, and space flight shall be accounted for, including: (1) load redistribution due to thermally induced deformations; (2) reduced material allowables; (3) changes in vibration modes and frequencies; (4) changes in tire and oleo strut pressures; and (5) changes in tire material properties (e.g., from runway friction).

5.2.11.1 LOADS

5.2.11.1.1 LANDING

The range of expected landing velocities and their distribution shall include provision for clearing a 50-ft obstacle with power off.

At least the following landing loads shall be accounted for:

- Maximum spin-up load and maximum spring-back load, each in combination with the vertical load occurring simultaneously. Dynamic analyses shall be made to obtain the necessary interrelations. Spin-up and spring-back loads shall be those loads developed when the sliding friction between the vehicle and landing surface equals 0.55 or any lower values that are critical. The touchdown speeds shall be all values from V_{SPA} to 1.3 V_{SPA}, but not less than 1.2 V_{SL}.
- Maximum vertical load, in combination with the drag load occurring at the instant of maximum vertical load. The drag load shall not be less than one quarter of the maximum vertical load. Aerodynamic lift, not exceeding the vehicle weight, may be assumed to exist during the initial landing impact and to act through the vehicle's center of gravity.

5.2.11.1.1.1 Symmetrical

Limit loads shall be determined for the weights of the applicable configurations in Sections 5.2.10.3 and 5.2.11.2, and for the following symmetrical landing attitudes at the design sink speed:

- Three-point landing, where the vehicle design permits the main and nose wheels to contact the ground simultaneously.
- Two-point landing, where the main wheels are in contact with the ground at the lowest possible pitch angle, with the nose wheel clear and not carrying load throughout the landing impact.
- Tail-down landing, where the vehicle is assumed to be at an attitude corresponding to either the stalling angle or the maximum angle allowing each part of the vehicle except the main wheels to clear the ground, whichever is less. If the vehicle is equipped with a tail bumper, the tail bumper shall be completely compressed and in contact with the ground, but with no load imposed on the vehicle.
- Nose-gear impact loads shall be determined from analysis of the vehicle motion during a landing in the tail-down attitude, with rational applications of brake and nose-down pitch control.

5.2.11.1.1.2 Unsymmetrical

Limit loads for unsymmetrical landing conditions shall include the effects of the vehicle motion in specified crosswind and landing velocities.

Experience indicates the yaw attitude should be that for a zero sideslip with a 5-deg roll attitude and a pitch attitude for a 1.1-g flare at a mean sink speed of 5 fps and a mean horizontal touchdown speed of 1.1 V_{SPA}.

Limit loads shall be determined for at least the unsymmetrical drift and one-wheel landing conditions.

In drift landing, the vehicle shall be in the two-point symmetrical landing attitude and (1) the vertical reaction at each main gear shall be one half of the maximum value defined for two-point symmetrical landing conditions; (2) the lateral load at one main gear shall consist of an

inward-acting load 0.8 times the vertical reaction at that gear; (3) the lateral load at the other main gear shall consist of an outward-acting load 0.6 times the vertical reaction at that gear; (4) the drag load shall be zero; and (5) all external loads shall be considered to act simultaneously at the ground and to be balanced by vehicle inertia.

In one-wheel landing, the vehicle shall be in the symmetrical two-point and tail-down landing attitudes and (1) the loads shall be applied alternately to each main landing gear with the drag and lateral loads equal to zero; (2) the load on the opposite main gear shall be zero; and (3) all external loads shall be considered to act simultaneously at the ground and to be balanced by vehicle inertia.

5.2.11.1.2 TAXIING AND BRAKING

Loads from taxiing and braking under the following conditions, as well as loads from all ground operations where the vehicle is operating independently under its own power, shall be accounted for. The vehicle shall be at its maximum flight gross weight (atmospheric). For the braking conditions, the landing gear and tires shall be in their static positions.

In straight taxi, the vehicle shall be in the three-point attitude. The drag loads and lateral loads shall be zero and the limit vertical-load factor shall be 2.0 g.

In turning, the vehicle shall be in the three-point attitude and shall execute steady turns by means of differential power or nose-gear steering. The vertical load factor at the center of gravity shall be 1.0; at the ground, lateral loads shall be applied so that the resultant of the vertical and side loads passes through the center of gravity; the ratio of the lateral load to vertical-load components shall be equal on all gears; and the sum of the lateral loads shall be one half the vehicle weight, except that the side loads need not exceed a value which would result in overturning.

In pivoting, the vehicle shall be in the three-point attitude, the vertical load factor at the center of gravity shall be 1.0, and the tire coefficient of friction shall be 0.8. With brakes locked on the wheels of one gear unit about which the vehicle is rotating, the vehicle shall pivot about the centroid of the contact area of all wheels in the gear unit.

In two-point and three-point braked rolls, the vertical load factor acting at the center of gravity shall be 1.2 at the landing configuration gross weight and 1.0 at the maximum configuration gross weight. A drag reaction at each brake-equipped wheel which is in contact with the ground shall be assumed to act at the ground equal to 0.8 of the vertical reaction and shall be combined with the vertical reaction.

In unsymmetrical braking, the vehicle shall be in the three-point attitude and the vertical load factor at the center of gravity shall be 1.0. One main gear shall be assumed to be braked and developing a drag load at the ground equal to 0.8 of the vertical reaction at that gear. The vehicle shall be placed in static equilibrium, with lateral loads at the main and nose gears reacting to the yawing moment, and with vertical loads at the main and nose gears reacting to the pitching moment. The forward-acting load at the center of gravity shall be 0.8 of the vertical reaction of the main gear which is braked. The lateral load at the center of gravity shall be zero, and the lateral load at the nose gear shall be acting at the ground and need not exceed 0.8 of the vertical reaction. The nose gear shall be aligned in a fore-and-aft direction.

In reverse braking, the vehicle shall be in a two-point attitude on the main gear, the vertical load factor at the center of gravity shall be 1.0, and a forward-acting drag reaction, acting at the ground equal to 0.8 of the vertical reaction, shall be combined with the vertical reaction for each gear equipped with brakes.

5.2.11.1.3 SUPPLEMENTARY

In addition to the loads imposed on landing-gear assemblies by landing, taxiing, and braking, at least the following loads shall be accounted for:

Rebound Loads. With the landing gear fully extended and not in contact with the ground, a rebound-load factor of -20.0 shall be assumed to act on the unsprung weight of the landing gear along the line of motion of the strut as it approaches the fully extended position.

Loads from Extension and Retraction of Landing Gear. With the landing gear in each critical position between fully extended and fully retracted, the loads shall consist of (1) aerodynamic loads up to the limit speed specified for the takeoff and landing configurations; (2) inertia loads corresponding to the maximum and minimum symmetrical limit-load factors specified for flight in the takeoff and landing configurations; (3) inertia loads resulting from maximum-powered accelerations of the landing-gear components that move during extension or retraction; and (4) gyroscopic loads

resulting from wheels rotating at a peripheral speed of 1.3 times the stalling speed in the takeoff configuration and the wheels retracting or extending at the maximum rate attainable.

Loads From Braking Wheels in Air. For the vehicle flying in the takeoff configuration with the landing gear in any position, the vertical load factor shall be 1.0. The airspeed and wheel peripheral speed shall be 1.3 times the stalling speed in the takeoff configuration. The maximum static braking torque shall be applied instantaneously to stop the wheel rotation.

Tail Bumper Loads. A dynamic analysis of motion shall be performed, considering: (1) that the vehicle rolls backward at 5 mph at zero ground slope and that the maximum braking load based on a tire-to-ground coefficient of friction of 0.8 shall be suddenly applied; and (2) that for landings, the attitude at touchdown shall be a tail-down landing condition with the main gear and bumper contacting the ground simultaneously.

5.2.11.1.4 LOAD DISTRIBUTION ON MULTIPLE WHEELS

The following loading distributions for landing gears having two wheels on one landing-gear unit shall be evaluated. A rational approach shall be used for landing-gear configurations having more than two wheels per unit.

For Symmetrical Distributions, the wheel loads shall be equally distributed among the wheels at each landing-gear unit.

For Unequal Tire Inflation, the wheel loads shall be distributed so that 60 percent are on one wheel and 40 percent on the other wheel, except in drift and turning conditions, when the 60-percent load need not be applied to the inboard wheel with the inward-acting lateral load nor to the outboard wheel with the outward-acting lateral load.

For Flat-Tire Landing, the wheel loads resulting from the landing conditions, reduced to 60 percent of the limit load, shall be applied to each wheel separately.

For Flat-Tire Taxiing, the wheel loads resulting from the taxiing conditions, reduced to 50 percent of the limit load, shall be applied to each wheel separately.

For Flat-Tire Towing, the wheel loads resulting from the towing conditions shall be applied to each wheel separately.

5.2.11.2 MASS PROPERTIES

The mass properties to be used for landing and horizontal takeoff conditions shall include all practical arrangements of variable and movable items and all gross weights indicated for atmospheric-flight configurations.

5.2.12 EMERGENCY CONDITIONS

Loads resulting from emergency conditions, including malfunction, abort, crash, and ditching, shall be accounted for.

5.2.12.1 MALFUNCTION

The transient conditions resulting from a malfunction shall be analyzed as a single event.

The analysis required for malfunction conditions should be conducted in conjunction with development of the malfunction-detection system, the malfunction-correction system, and the abort-initiation system. Based on the structural design requirements and the analysis of probabilities associated with malfunctions, the allowable bounds of the parameters defining the malfunction condition and the related time limits should be established. For cases where system performance is incompatible with the time limits, data relative to the tradeoff between mission degradation due to added weight and increased risk should be assembled to facilitate a choice.

5.2.12.2 ABORT

The transient conditions resulting from abort shall be analyzed as a single event, considering probabilities of occurrence of all loadings and environmental parameters and allowable risk for abort.

The analysis required for abort conditions, conducted in conjunction with development of the abort system and procedures, should include the following:

- Transient conditions resulting from emergency staging and separation of the two shuttle vehicles at any time after liftoff or from another vehicle in space.
- Effects of emergency systems and procedures (e.g., auxiliary propulsion or propellant dump) developed to facilitate return of the vehicle to a stable cruise-flight condition.
- Initial transient and the subsequent flight conditions for personnel-escape systems, such as ejection seats or escape pods.

All structural weight penalties imposed by abort conditions should be identified and submitted to NASA for approval.

5.2.12.3 CRASH

The ultimate crash-load factors relative to body axes indicated in the following table shall be used in design of structure whose failure could result in injury to personnel during a crash or prevent egress from a crashed vehicle:

Area	Load Factor Longitudinal	Vertical	Lateral
Crew and passenger compartments	+40	±20	±7
Cargo and equipment areas	+10	+5	–
Large mass equipment-support structure	+9 -1.5	-2.0 +4.5	+1.5 -1.5

The specified load factors are in the direction of the acceleration. Plus refers to forward, down, or right. Longitudinal load factor shall be directed forward within a 20-deg semiangle cone whose axis is the vehicle's longitudinal axis.

Fuel tanks shall be considered to contain that cruise fuel which remains after one half of the total internal cruise fuel has been expended in the normal manner. The boost or orbit-injection fuel shall not be included.

See Section 4.10.9.

5.2.12.4 DITCHING

The ultimate normal water pressures resulting from ditching, which are indicated in the following table, shall be accounted for in design of local structure.

Area	Longitudinal Station, percent	Pressure Over Lower Half of Fuselage, psi	Pressure Over Upper Half of Fuselage, psi
(a)	0 – 5	15	15
(b)	5 – 10	15	6
(c)	10 – 25	15	0
(d)	25 – 60	15	0
(e)	60 – 80	15	0

The areas over which these pressures should be considered to act are indicated in the second column in terms of bounded longitudinal stations (as a percentage of the overall length of the vehicle aft of the most forward portion of vehicle structure). Simultaneous loading should be assumed for the structure covering the following combinations of areas: (a) and (b), (b) and (c), (c) and (d), and (d) and (e).

See Section 4.10.9.

6. NATURAL AND MAN-MADE ENVIRONMENTS

6.1 ATMOSPHERIC PROPERTIES

6.1.1 BELOW 90 KM ALTITUDE

The atmospheric models defined in NASA TM X-53872 (Sec. 14) shall be used to represent the prelaunch, launch, and ascent phases in analyses of space flights launched from any launch site.

The atmospheric models based on the Cape Kennedy Reference Atmosphere include: (1) the nominal atmosphere; (2) extreme gas properties; (3) extreme profiles of gas properties; and (4) thermodynamic quantities associated with extreme values of pressure, temperature, and density.

The U.S. Standard Atmosphere (1962) and Supplements (1966), as expanded in NASA TM X-53872, shall be used for analyses of atmospheric flight and entry flight at altitudes below 90 km and for analyses of all ground operations.

Mean values are given in the U.S. Standard Atmosphere Supplements. Extreme densities are given in Section 14 of NASA TM X-53872. Atmospheric models in this NASA document are appropriate to computation of instantaneous vehicle heating, accumulated vehicle heating, and the effect on heating of extreme density changes with latitude and altitude.

6.1.2 ABOVE 90 KM ALTITUDE

The atmospheric model defined in NASA TM X-53957 (Sec. 2.2) shall be used during the space, entry, or emergency phases occurring above 90 km.

6.2 WINDS AND GUSTS

The wind environment (e.g., wind speed, shear, gusts, and turbulence) defined in NASA TM X-53872 shall be used for analyses of wind effects on the vehicle.

The following recommendations should be considered as guides for the application of wind-environment parameters to structural design:

Prelaunch Phase. The prelaunch winds should be as follows:

1. Peak winds at 18.3 m corresponding to a 1-percent risk of exceedance, together with a 3σ wind profile, for the windiest two-week exposure period, considering both Eastern and Western Test Ranges. Winds are assumed to be from any azimuth.
2. Mean wind profiles over a 10-min. period, corresponding to a 1-percent risk for the windiest two-week period, combined with ground wind turbulence. Both Eastern and Western Test Ranges should be considered. Winds are assumed to be from any azimuth.

Applicable peak winds and the associated 3σ profile are given in table 6-1, and correspond to a velocity of 72.1 knots at a reference level of 18.3 m.

Peak wind profiles below 72.1 knots are given by the following relationship:

$$U(h) = U_{18.3} \left[\frac{h}{18.3}\right]^{1.6 \left(U_{18.3}\right)^{-\frac{3}{4}}}$$

where

$U(h)$ = peak wind speed at height h meters above grade

$U_{18.3}$ = wind speed at the 18.3-m reference level.

The 10-min. mean wind profiles to be used for combination with turbulence, and which correspond with the 72.1-knot peak wind at the reference level, are given in table 6-2.

To calculate 10-min. mean wind profiles for reference-level peak winds below 72.1 knots, the following relationship should be used:

$$\bar{U}(h) = U(h)\left[1 + \frac{(18.3/h)^{0.283-0.435^{-0.2\,U_{18.3}}}}{1.98 - 1.887^{-0.2\,U_{18.3}}}\right]^{-1}$$

where

$\bar{U}(h)$ = the mean wind speed at height h

$U(h)$ = the peak wind speed at height h

$U_{18.3}$ = the peak wind speed at the 18.3-m reference level

TABLE 6-1 DESIGN PEAK WIND-SPEED PROFILES FOR A 1% RISK OF EXCEEDING THE 18.3-M REFERENCE LEVEL PEAK WIND SPEED FOR THE WINDIEST TWO-WEEK EXPOSURE PERIOD

HEIGHT		WIND SPEED	
(m)	(ft)	(m sec^{-1})	(knots)
18.3	60	37.1	72.1
30.5	100	39.1	76.1
61.0	200	42.1	81.9
91.4	300	44.0	85.5
121.9	400	45.4	88.2
152.4	500	46.5	90.3

TABLE 6-2 10-MIN. MEAN DESIGN WIND PROFILE ASSOCIATED WITH THE 1% RISK PEAK WIND PROFILE FOR THE WINDIEST TWO-WEEK EXPOSURE PERIOD

HEIGHT		WIND SPEED	
(m)	(ft)	(m sec^{-1})	(knots)
18.3	60	24.7	47.9
30.5	100	27.2	53.0
61.0	200	31.0	60.3
91.4	300	33.3	64.8
121.9	400	35.1	68.1
152.4	500	36.4	70.7

For combination with 10-min. mean wind profiles, the turbulence is described by spectral methods. The turbulence is represented by two components in the horizontal plane, parallel and perpendicular to the steady wind. The longitudinal and lateral spectra of turbulence at frequency ω and height h are represented by the dimensionless form:

$$\frac{\omega S(\omega)}{\beta U_*^2} = \frac{c_1 f/f_m}{\left[1 + 1.5 (f/f_m)^{c_2}\right]^{\frac{5}{3} c_2}}$$

where

$f = \omega h/\bar{U}(h)$

$f_m = c_3 \, (h/h_r)^{c_4}$

$\beta = (h/h_r)^{c_5}$

$U_* = c_6 \, \bar{U}(h_r)$

$h_r = 18.3$ m

$\bar{U}(h)$ = 10-min. mean wind speed at height h

The constants c, from NASA TM X-53872, are as follows:

	Longitudinal	Lateral
c_1	6.198	3.954
c_2	0.845	0.781
c_3	0.03	0.10
c_4	1.00	0.58
c_5	0.63	0.35
c_6	0.0973	0.0973

The power-spectral ground-wind-turbulence model should be used to calculate elastic-vehicle ground-wind gust loads. Application of the model will yield the power spectra of the pertinent load parameters. Integration of these load spectra over the frequency domain ($0 \geqslant \omega \geqslant \infty$) will yield the variance of the loads. The associated design turbulence loads should be obtained by multiplying the standard deviations of the load by a factor of 3. The resultant elastic-vehicle design loads should be obtained by addition of the turbulence loads and the steady loads calculated from the 10-min. mean wind profiles.

The cospectrum and quadrature spectrum associated with either the longitudinal or lateral components of turbulence at levels h_1 and h_2 are represented by:

$$C(\omega, h_1, h_2) = \sqrt{S_1 S_2} \exp - \left(0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \cos (2\pi\gamma\Delta f)$$

and

$$Q(\omega, h_1, h_2) = \sqrt{S_1 S_2} \exp - \left(0.3465 \frac{\Delta f}{\Delta f_{0.5}}\right) \sin (2\pi\gamma\Delta f)$$

where

$$\Delta f = \frac{\omega(h_2)}{u(h_2)} - \frac{\omega(h_1)}{u(h_1)}$$

where

S_1 = the longitudinal spectrum at level h_1

S_2 = the lateral spectrum at level h_2

$u(h_1)$ and $u(h_2)$ = the quasi-steady wind speeds at levels h_1 and h_2, respectively

$\omega(h_1)$ and $\omega(h_2)$ = the frequency at levels h_1 and h_2, respectively

where

Turbulent Component	Longitudinal	Lateral
$(h_1 + h_2)\gamma/2 \leqslant 100$ m	0.7	1.4
$(h_1 + h_2)\gamma/2 > 100$ m	0.3	0.5
$\Delta f_{0.5}$	0.036	0.045

Launch and Landing Phase. The winds at launch and during landing should be as follows:

1. Peak winds at 18.3 m corresponding to a 5-percent risk, together with a 3σ peak wind profile, for the windiest hourly exposure based on a monthly reference period. Winds should be measured before launch so that this condition is a risk of launch delay only.

2. Wind shear resulting from the above peak wind at the top of the vehicle and the associated 10-min. mean wind at the base of the vehicle.

The peak wind profile for the above conditions is given in table 5.2.13 of NASA TM X-53872, while the corresponding 10-min. mean wind profile is given in table 5.2.21 of the same document. Wind shear should be determined by subtracting the 10-min. mean wind speed at the base of the vehicle from the peak wind speed at the top of the vehicle, and dividing the difference by the vehicle height.

Ascent Phase and Booster-Entry Phase. The winds during ascent and booster entry should be as follows:

1. The 5-percent risk of launch delay for the steady-state horizontal wind-speed profile of table 6-3.

2. Wind-shear values given in tables 5.3.20 and 5.3.21 of NASA TM X-53872.

3. A discrete gust for rigid-body analyses having a 1-cos shape with a 9-m/sec amplitude and a thickness of 60 to 300 m. Various gust thicknesses between these limits should be examined to determine the critical design value.

To obtain a 1-percent-risk condition under the combined wind shear and discrete gust, both should be multiplied

by a factor of 0.85 before they are combined with steady winds to produce a synthetic wind profile. This factor recognizes that 1-percent-risk gusts and 1-percent-risk wind shears will not be perfectly correlated.

The procedure to be followed to produce a synthetic wind profile is given in Section 5.3.9.2 of NASA TM X-53872.

The turbulence power spectrum to be used instead of discrete gusts for elastic-vehicle studies is given by the expression:

$$E(k) = \frac{777.2(4000K)^{1.62}}{1 + 0.0067\,(4000K)^{4.05}}$$

where E(k) is the power spectral density ($m^2 sec^{-2}$/cycles m) at wave number K (m^{-1}). Integration over the domain $0 \leqslant k \leqslant \infty$ yields the variance of the turbulence. The associated design-turbulence loads should be obtained by multiplying the load's standard deviations by a factor of 3. The loads obtained from application of this turbulence power spectrum should be added to the loads resulting from the use of the synthetic wind profile, less discrete gusts.

Orbiter-Entry Phase. Wind, wind-shear, and gust conditions for the orbiter-entry phase should be the same as for the ascent and booster-entry phases, except that the 1-percent-risk idealized scalar wind-speed profile given in table 6-4 should be used instead of table 6-3.

TABLE 6-3 **DESIGN STEADY-STATE WIND-SPEED PROFILE ENVELOPE FOR BOOST AND BOOSTER-RETURN PHASES**

GEOMETRIC ALTITUDE (km)	WIND SPEED (m sec^{-1})
1	21
10	75
14	75
20	25
23	25
60	126
80	126

TABLE 6-4 **DESIGN STEADY-STATE WIND-SPEED PROFILE ENVELOPE FOR ORBITER-ENTRY PHASES**

ALTITUDE (km)	WIND SPEED (m sec^{-1})
150	200
115	200
80	150
60	150
23	40
20	40
14	97
10	97
1	28

Atmospheric-Flight Phase. Gusts during atmospheric flight should be as follows:

1. Atmospheric gusts with a 1-percent risk of structural compromise, on a limit-load basis, for 100 hours of flight time, if a ferrying capability is not included.
2. Atmospheric gusts with a 1-percent risk of structural compromise, on a limit-load basis, for 1000 hours of flight time, if a ferrying capability is included.

The normalized power spectra of atmospheric turbulence should be:

Longitudinal $\Phi_u = \frac{2L}{\pi} \frac{1}{\left[1 + (1.339L\Omega)^2\right]^{\frac{5}{6}}}$

Vertical and lateral $\Phi_w = \frac{L}{\pi} \frac{1 + 8/3\,(1.339L\Omega)^2}{\left[1 + (1.339L\Omega)^2\right]^{11/16}}$

Now

$$A = \left[\int_0^\infty \Phi_N(\Omega)\left|T(\Omega)\right|^2 d\Omega\right]^{\frac{1}{2}} \frac{\text{Units of load parameter}}{\text{ft sec}^{-1}}$$

$$N_0 = \frac{V}{2\pi A}\left[\int_0^{\infty} \Omega^2 \, \Phi_N(\Omega)|T(\Omega)|^2 \, d\Omega\right]^{\frac{1}{2}} \frac{\text{cycles}}{\text{sec}}$$

where

A = the ratio of rms response to rms gust velocity

$T(\Omega)^2$ = the square modulus of the frequency-response function for a load parameter of interest y

Φ_N = the normalized power spectra of atmospheric turbulence

N_0 = the characteristic frequency of the response

V = the vehicle speed, and

$$M(y) = \sum_{i=1}^{K} N_{0_i} \frac{t_i}{T}\left(P_{1_i} e^{-y/A_i b_{1_i}} + P_{2_i} e^{-y/A_i b_{2_i}}\right)$$

where

$M(y)$ = the cumulative cycles per second equaling or exceeding the load parameter y

P_1 and P_2 = the proportions of time in normal and severe turbulence, respectively

t_i = the amount of time spent in the i^{th} segment of the mission

T = the total time flown by the vehicle over all K mission segments

Now a 1-percent risk for 100 hours (nonferrying) or 1000 hours (ferrying) corresponds to a rate of load exceedance equal to 2.78×10^{-6} sec^{-1} (nonferrying) or 2.78×10^{-7} sec^{-1} (ferrying). To obtain the limit value of any load parameter y, these numerical values are therefore substituted for M(y) into the above equation.

Values of N_0 and A should be determined for various load parameters throughout the structure, and the equation for M(y) solved for limit values of each of these parameters.

Values of P_1, P_2, b_1, b_2, and L all vary with altitude and are given in Section 5.3.12 of NASA TM X-53872.

6.3 RAIN

The rain environment defined in NASA TM X-53872 (tables 4.1 and 4.4) shall be used in evaluation of the accumulated damage from rain. The total vehicle exposures to rain shall be consistent with the data of table 4.3 of NASA TM X-53872 and with the specified intervals between refurbishment of components.

6.4 HAIL

The number of vehicle exposures to hail and the severity and duration of such exposures shall be specified for an evaluation of the potential damage from cumulative effects of hail. As an alternative, the hail environment which the vehicle must withstand or be protected against shall be equivalent to a single exposure to 50 mm (2 in.) of hail over a duration of 15 min., with a velocity of fall of 30.5 m/sec, mass density of 0.80 g/cm^3, and wind speed of 10 m/sec.

Size distributions shall be

Diam Range, centimeters	**Number of Hailstones per cubic meter**
0-1	**22.0**
1-2	**0.8**
2-3	**0.17**

Variation in hail hardness with temperature shall be as indicated in NASA TM X-53872, table 6.2.

6.5 BLOWING SAND AND DUST

Blowing sand and dust environments which the vehicle must withstand or be protected against shall be as defined in NASA TM X-53872 (Sec. 6).

Particle size, hardness, and distribution are indicated in the NASA document for windblown sand and dust. If qualification tests in a windblown-sand environment are required, the following conditions should be used: particle size, 0.08 to 0.12 mm; hardness, 7 to 8 moh; distribution, 0.02 g/cm^3; wind speed, 10 m/sec; duration of exposure, 10 hr.

If qualification tests in a windblown-dust environment are required, the following conditions should be used: particle size, 0.0001 to 0.0002 mm; hardness, 7 to 8 moh; distribution 6×10^{-9} g/cm^3; wind speed, 10 m/sec; duration of exposure, 10 hr.

6.6 SALT AIR ENVIRONMENT

A model of the salt air environment which the vehicle must withstand shall be specified.

6.7 HUMIDITY

The humidity which the vehicle must withstand shall be specified.

6.8 FUNGI

A model of the fungi which the vehicle must withstand or be protected against shall be specified.

6.9 ATMOSPHERIC CONTAMINANTS

The atmospheric contaminants which the vehicle must withstand shall be specified.

The contaminants which may be present in the atmosphere at the various localities in which the vehicle will operate (e.g., industrial and commercial contaminants and automobile-exhaust products) should be included.

6.10 ATMOSPHERIC ELECTRICITY

Atmospheric electric phenomena which the vehicle must withstand or be protected against shall be as defined in NASA TM X-53872, Section 9, including lightning strike on the ground, inflight-triggered lightning, and static electrical charge.

The maximum peak current due to lightning strike on the ground is defined as 100 000 amp 90 percent of the time. The peak current flow is reached in 10 μsec after the start of the stroke, falling to one half the peak value in 20 μsec. A total stroke charge of 100 coulombs is transmitted to earth with 95 percent of the current flow, after initiation of the first stroke, at less than 5000 amp.

The characteristics of inflight-triggered lightning strike are the same as for lightning strike on the ground, except that the average current flow will remain at a value of 185 amp for at least 175 msec before falling to zero.

No values are given for allowable static electrical charge since the buildup of such charge can be avoided by the design methods given in Rain Erosion and Associated Phenomena, Vol. 2, and in MIL-B-5087B (ASG).

6.11 SOLAR THERMAL RADIATION

The following solar thermal-radiation intensities shall be used for heat-transfer evaluation:

- Space Phase. 2.00 g-cal/cm^2-min normal to the direction of the sun, with the distribution of radiation with wavelength as given in table 2.1 of NASA TM X-53872.
- Ascent, Entry, and Atmospheric Phases. The value given for the space phase reduced by the effect of atmospheric absorption, but increased by the diffuse radiation from the sky.

  Assumption of a clear sky is generally conservative.
- Ground Phases. 1.79 or 1.84 g-cal/cm^2-min normal to the direction of the sun (for the Eastern and Western Test Ranges, respectively), whichever is critical.

6.12 ALBEDO

A model of albedo for earth, moon, and objects in cislunar space shall be specified.

6.13 ELECTROMAGNETIC AND PARTICULATE RADIATION

The radiation environment from both natural and onboard sources shall be specified. The definition shall be based on reliable and current information on the type, intensity, energy spectrum, temporal variation, and spatial distribution of the environment. Radiation sources shall include neutrons, protons, and heavier ions, electrons, and photons (gamma rays, X-rays, and ultraviolet rays).

6.14 METEOROID ENVIRONMENT

The meteoroid environment which the vehicle must withstand shall be as defined in NASA TM X-53957, Section 2.5.

Included in the meteoroid environment are models of particle density, velocity, and flux for total, sporadic, and derived stream meteoroids. Additional information on the meteoroid environment is given in NASA SP-8013.

6.15 NOISE

Noise levels and spectra from all external and internal sources which the vehicle must withstand shall be specified.

6.16 RUNWAY AND TAXIWAY ROUGHNESS

A model for runway and taxiway roughness to be used in evaluation of ground loads shall be specified.

7. PROOF OF DESIGN

Proof of structural adequacy of the design under all anticipated loads and environmental conditions shall be provided by appropriate analyses and tests, which shall be documented.

7.1 DOCUMENTATION

Reports shall be prepared on analyses and tests conducted to verify the structural adequacy of the design. Assumptions, methods, and data used shall be defined. References cited in the reports which are not readily available shall be submitted to NASA with the reports. Reports shall cover at least the following:

- Integrated plan for proving structural adequacy
- Analyses
- Tests
- Structural physical characteristics
- Definition of structural interfaces
- Operating restrictions
- Inspection and repair
- Operational usage measurements.

7.1.1 INTEGRATED PLAN

An integrated plan shall be prepared which describes the total plan for verifying structural adequacy and includes schedules for accomplishment. The plan shall be revised as necessary to reflect changes in schedules, requirements, objectives, design characteristics, and operational usage.

7.1.2 ANALYSES

Reports shall be prepared on analyses performed to verify structural adequacy. The reports shall be divided logically by subject and shall include results of at least the following: (1) loads analyses; (2) thermal analyses; (3) stress analyses; and (4) structural dynamic response and stability analyses.

7.1.3 TESTS

Test plans and test reports shall be prepared for all tests, including tests to determine design loads, pressures, or environments; tests to characterize materials, structural components, or assemblies; development tests; qualification tests; acceptance tests; flight tests; and special tests. (See Sections 7.3 through 7.9.)

7.1.3.1 TEST PLANS

A comprehensive test plan shall be prepared for each test prior to conducting the test. The plan shall include a description of the test purpose, articles, requisite data, instrumentation, setup, conditions, accept-reject criteria, and provisions for complete documentation. Test plans shall be approved by NASA.

For flight tests, each test plan shall show how the test data will be extrapolated and interpreted in terms of design requirements when the test is conducted in a noncooperative natural environment (such as where actual wind velocities are a small fraction of the velocities corresponding to limit load).

7.1.3.2 TEST REPORTS

Test reports shall include the test results, conclusions, and recommendations; also, in case of failure, these reports shall describe the failure, the failure condition, the cause of failure, and the corrective action taken.

7.1.4 STRUCTURAL PHYSICAL CHARACTERISTICS

The physical characteristics of the booster and orbiter which are significant to the design of the vehicle structure shall be described and controlled by appropriate documentation, procedures, and policies. The physical description in the documentation shall include at least the following data for each stage: (1) vehicle dimensions; (2) aerodynamic-surface areas; (3) station locations; (4) unit weights; (5) weight distributions; (6) centers of gravity; (7) distribution of mass, inertia, and stiffness; (8) vibration modal data; and (9) detailed configuration dimensions (e.g., flange widths or thickness). The detail and accuracy of the documentation shall be sufficient to provide the basis for all structural analysis.

7.1.5 INTERFACES

Physical and functional interfaces of the structure and other components, assemblies, systems, liquids, and gases shall be identified in the documentation. Interfaces within each vehicle, between vehicles, and with external

vehicles and test equipment shall be accounted for. Methods of controlling and accounting for interfaces shall be defined.

7.1.6 OPERATING RESTRICTIONS

Reports shall be prepared on vehicle-operating restrictions which state the strength of the structure and any limitations on preparation, testing, and operational use of the vehicle.

The reports should be subdivided into sections applicable to significant operating regimes for ready reference, such as: (1) atmospheric flight, (2) prelaunch handling, (3) pad or range safety, (4) launch and ascent, (5) orbital operations, (6) entry and recovery, and (7) emergency operations.

7.1.7 INSPECTION AND REPAIR

Reports shall be prepared on inspection and repair of the vehicle. The reports shall include: techniques for inspection of structure for the purpose of locating hidden defects, deteriorations, and fatigue effects; and repair and replacement instructions, modified as necessary on the basis of flight-test experience.

7.1.8 OPERATIONAL-USAGE MEASUREMENTS

A plan for measurement of loads and temperatures during vehicle operation shall be developed.

Reports shall be prepared on operational-usage measurements. These reports shall define the recording and monitoring systems for evaluating structural adequacy during operational usage. In case of failure, these reports shall describe the failure, the failure condition, the cause of failure, and the corrective action taken.

7.2 ANALYSES

Analyses shall be performed to verify structural adequacy in compliance with the criteria of Sections 4 through 6. Where adequate theoretical analysis does not exist or where experimental correlation with theory is inadequate, the analyses shall be supplemented by tests.

At least the following analyses shall be performed:

1. Loads analyses covering the loads and environments expected to be imposed on the vehicle during its service life. All critical loads and combinations shall be defined. Analyses shall account for (a) vehicle geometry; (b) flight conditions such as altitude, velocity, and load factors; (c) weight conditions; (d) inertial properties; (e) vehicle and control-system stiffness distributions; (f) vehicle vibration-mode frequencies and structural damping; (g) structural interaction with the control system; (h) variation of loads with time for deterministic load analyses; and (i) all statistical loadings for probabilistic load analyses. Computed static and dynamic loads shall be combined with thermal effects to produce vehicle-critical design loads, vehicle-test loads, and data for use in establishing strength and operating restrictions on the vehicle.

2. Thermal analyses of structural response to the anticipated thermal environment. Steady-state and transient thermal analyses shall be performed in compliance with the criteria presented in Sections 4 through 6. These analyses shall account for the following in all the phases of the vehicle's life: flight conditions which affect heating (such as maximum heating trajectories, aerodynamic heating, exhaust-plume heating from the propulsion and control systems, propellant-tank levels, and orbit definition and orientation); and configuration description (such as structural materials and their properties, structural components and their assembly, insulation materials, and internal energy sources).

3. Stress analyses covering structural response to the critical loads, environments, and temperatures anticipated during the service life of the vehicle. These analyses shall define the critical combination of loads, conditions, material properties, and interactions which determine stress levels and margins of safety for all structural components. Analyses shall also be performed to show that deformations do not cause degradation of vehicle performance. Stress analyses shall also provide data for use in establishing vehicle strength and operating restrictions.

4. Structural dynamic response and stability analyses. These analyses shall account for the following in all phases of the vehicle's life: vehicle geometry, flight conditions, weight conditions and corresponding mass properties, vehicle and control-system stiffness distributions, structural interaction with the control system, stationary and nonstationary aerodynamic coefficients, structural interaction with the propellant system, interface with thermal characteristics, and stability margins.

7.3 TESTS TO DETERMINE LOADS, PRESSURES, AND ENVIRONMENTS

Tests shall be conducted to assist in defining or verifying static and dynamic design loads, pressures, and environments which the vehicle will encounter through its service life. Tests shall be performed in accordance with the criteria of Sections 4 through 6.

7.3.1 AIR LOADS AND PRESSURES

Wind-tunnel tests shall be performed to verify analytical estimates of the aerodynamic coefficients and pressures. Proper allowance shall be made for scaling effects. These tests shall cover the vehicle operational speed, altitude, and angle-of-attack range. Load redistribution for the aeroelastically deformed vehicle shall be accounted for. Variation of local pressures with time at vent locations shall also be obtained.

For recommended practices, see NASA SP-8006, and a forthcoming NASA special publication on compartment venting.

7.3.2 GROUND WIND LOADS

Dynamically similar wind-tunnel models of the vehicle and its restraint on the launch pad shall be used to obtain ground wind loads. The vehicle model shall incorporate all protuberances. The influence of adjacent towers and launch equipment shall be accurately simulated. Tests shall be conducted on both mated and unmated configurations for all orientations with respect to the wind at both subcritical and supercritical Reynolds numbers.

Full-scale ground wind loads shall also be measured to establish the validity of the wind-tunnel tests and analyses.

Refer to NASA SP-8008 and AFSC DH 3-2 (DN 3A3) for recommended practices.

7.3.3 BUFFET LOADS

Dynamically similar wind-tunnel models of the mated and unmated vehicles shall be tested to obtain buffet loads. Each ratio of the model to full-scale Mach number, to reduced frequency, and to Reynolds number (if possible) shall be unity. The tests shall cover the vehicle speed, altitude, and angle-of-attack range.

For recommended practices, refer to NASA SP-8001 and NASA CR-1596.

7.3.4 SLOSH LOADS

Scale-model tests shall be conducted on both mated and unmated configurations to obtain fuel sloshing loads and to validate the effectiveness of the slosh-suppression devices used. Inertial, viscous, and interfacial characteristics of the liquid shall be scaled.

Full-scale vehicle slosh tests may also be required to verify the model-test results.

Refer to NASA SP-8009 and SP-8031 for recommended practices.

7.3.5 SHOCK LOADS

Mechanical-shock tests shall be conducted to define the shock environment when it is not predictable by analysis or previous tests, and to develop means for reducing excessive shock levels.

The tests should be conducted on full-scale structural components and assemblies. For recommended practices, refer to NASA SP-8043, forthcoming NASA special publications on protection against explosive shock and mechanical shock response analysis, MIL-A-8867(ASG), and AFSC DH 3-2 (DN 4C3).

7.3.6 ACOUSTIC LOADS

Acoustic tests shall be conducted to define the acoustic environment when this cannot be done by analysis or previous tests on similar structure, and when there is a need to develop means for reducing acoustic-load damage.

The tests should be conducted on full-scale structural components and assemblies in an accurately simulated service environment.

For recommended practices, refer to NASA SP-8043, NASA CR-1596, and AFSC DH 3-2 (DN 4C4).

7.3.7 VIBRATION

Tests shall be conducted to define the vibration environment and to develop techniques for suppressing excessive vibration.

The tests should be conducted on full-scale structural components and assemblies in an accurately simulated service environment.

For recommended practices, refer to NASA SP-8043, NASA CR-1596, and a forthcoming NASA special publication on structural vibration prediction.

7.3.8 MODAL SURVEY

Full-scale ground vibration tests shall be conducted to verify the vehicle's vibration modes, frequencies, and damping coefficients used for dynamic-load and dynamic-aeroelastic calculations. The vehicle shall be properly supported so that its rigid-body frequencies are noticeably lower than its free-free flexible-body frequencies. Mass configurations shall conform to those found to be critical from theoretical analyses. The tests

shall be performed to obtain all significant symmetric, antisymmetric, and unsymmetric vibration modes and frequencies. Instrumentation shall be used to measure all significant coupling responses.

Refer to NASA SP-8012, SP-8016, SP-8036, SP-8043, NASA CR-1596, MIL-A-8870(ASG), and AFSC DH 3-2 (DN 4C7) for recommended practices.

7.3.9 HEATING

When analysis is not adequate to evaluate external heating sources, tests shall be conducted to verify the analytical models of heat-transfer parameters in accordance with the criteria of Sections 4.6 and 5.2.

Tests shall be conducted to evaluate the external heating sources in at least the following: (1) areas adjacent to protuberances; (2) wake areas downstream of protuberances; (3) separated-flow and reattachment areas; (4) shock-wave impingement areas; (5) areas of base heating; and (6) areas subjected to three-dimensional exhaust plumes or to plume impingement.

Tests should be conducted on reduced-scale models or on full-scale components and assemblies under accurately simulated flight conditions. A number of tests will be required to evaluate the various parameters of interest.

7.4 MATERIAL CHARACTERIZATION TESTS

When structural material characteristics, including physical and allowable mechanical properties and failure mechanisms, are not available in NASA-approved references, tests shall be performed to characterize the materials in accordance with the criteria of Sections 4.7.1, 4.7.2, and 4.7.3.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, MIL-HDBK-5A, and AFML-TR-66-386.

7.4.1 PHYSICAL PROPERTIES

Material physical properties, including thermal properties, shall be determined by experiment.

Physical properties should include, as appropriate: density, coefficient of thermal expansion, thermal conductivity, specific heat, solar absorptance, and infrared emittance.

For recommended practices, refer to NASA SP-8014, SP-8043, NASA NHB 8080.3, MIL-A-8860(ASG), MIL-STD-143A, MIL-STD-810B, and ASTM E 332-67.

7.4.2 ALLOWABLE MECHANICAL PROPERTIES

Allowable mechanical properties shall be determined by experiment.

Mechanical properties should include allowable values for tensile and compressive yield strength, tensile and compressive ultimate strength, bearing and shear strengths, moduli of elasticity, and material elongation. Sufficient test data should be obtained to account for scatter in the data. Where applicable, inspection procedures, accept-reject criteria, the effect of manufacturing processes on material properties, and protective-surface treatments should be determined.

7.4.3 FAILURE MECHANISMS

Tests shall be performed on structural materials to determine their susceptibility to failure by the failure mechanisms of Section 4.7.3. The following failure mechanisms shall be determined by test, as applicable:

- **Fatigue**
- **Brittle fracture**
- **Hydrogen embrittlement**
- **Temper embrittlement**
- **Stress-corrosion cracking**
- **Creep**
- **General corrosion**
- **Galvanic corrosion**
- **Meteoroid-impact damage**
- **Radiation damage**
- **Protective finishes and surface treatments.**

Fatigue. **The fatigue characteristics of structural materials, components, and, in some cases, full-scale assemblies, shall be determined by test. These tests shall be made in the design-combined environment representing static loads, dynamic loads, temperature, vacuum, and/or corrosion. Provisions shall be made to reduce allowable stresses to account for scatter in the test data.**

The test loading conditions, environments, and stress states should represent as accurately as possible those expected during the service life of the structure.

Brittle Fracture. The brittle-fracture properties of thick-wall and heavy-forged sections will be required for the vehicle structural design. The tentative standard testing procedures developed by ASTM Committee E-24 should be applied.

In conjunction with evaluation of brittle fracture, fracture toughness should be determined by experiment. For materials selected for metallic pressure vessels, flaw-growth characteristics and threshold stress intensity should be experimentally determined.

When experimentally determining the fracture toughness of materials, the test specimens should be sufficiently wide to prevent in-plane bending and should be of the same material and thickness as the pressure vessels, and processed in the same manner. A sufficient number of specimens having flaws of various sizes and simulating the parent metal, weldments, and heat-affected zones of the pressure vessels should be tested to allow meaningful statistical values of fracture toughness to be established.

When experimentally determining the flaw-growth characteristics of material selected for metallic pressure vessels, the test specimens should be of the same material as the pressure vessels, sufficiently wide to prevent in-plane bending, and sufficiently thick to ensure that flaws attain critical size before growing more than halfway through the thickness of the test specimens. Sufficient tests should be conducted in the simulated service environment to allow meaningful statistical values of flaw-growth characteristics to be estimated for the parent metal, weldments, and heat-affected zones of the pressure vessels.

When experimentally determining the threshold stress-intensity characteristics of materials selected for vessels subjected to sustained pressure, the specimens should be tested in environments simulating the actual service environments as nearly as practicable. A sufficient number of specimens should be tested to allow meaningful statistical values of the material's threshold stress intensities to be established.

For recommended practices, refer to NASA SP-8040.

Hydrogen Embrittlement. Sustained load-carrying ability of metals (particularly steels and titanium alloys) susceptible to hydrogen embrittlement should be evaluated by laboratory tests.

A variety of specimen configurations such as the prestressed bent beam, split-ring, and notched types can be used. Safe threshold working-stress levels may be established for materials susceptible to hydrogen-induced embrittlement by subjecting specimens to the operational hydrogen environment. Safe or tolerable levels of hydrogen absorption should be determined for titanium alloys. The effects of possible hydrogen absorption from fabrication processes such as chemical milling, pickling, and cleaning prior to plating should be determined for steel and titanium alloys. For steel alloys, no dangerous or embrittling levels of absorption should be permitted to occur from these processes. For titanium alloys, the level of hydrogen absorbed during processing should be determined by hydrogen analyses. This level must be safely below the previously determined tolerable limits.

Temper Embrittlement. Tests should be made on representative coupons to verify that temper embrittlement has not occurred.

Stress-Corrosion Cracking. There are no universally accepted test procedures to determine stress-corrosion cracking. The test-sample configurations most often used are identical to those previously mentioned for hydrogen-embrittlement tests. Short-time cyclic immersion in salt water and exposure to the sea-salt environment are the most common types of tests.

The synthetic sea-water solution used should be as designated by the American Society of Testing Materials. Other corrosive environments such as air, gas, or fuel can also be used for test conditions, where appropriate.

Creep. Creep tests for candidate structural materials should be conducted at elevated temperatures unless valid comparisons can be made from results of prior tests that are acceptable to NASA. Standard procedures of the American Society of Testing Materials should be followed for creep tests on materials. (There are no established standard procedures for such tests on structural assemblies.)

The effects of temperature overshoot on the creep properties of sensitive materials should be determined.

General Corrosion. Typical corrosion tests for evaluating material susceptibility to surface pitting and oxidation may be made using the well-known outdoor

seashore rack for mounting unloaded panels. Structural material samples and small assemblies may be subjected to the salt-spray simulation test described in MIL-STD-810B.

Galvanic Corrosion. There are no standard tests for galvanic corrosion.

Meteoroid-Impact Damage. **If appropriate data do not exist, material constants such as K_∞ and K_1, used in analyses of meteoroid penetration, shall be determined from hypervelocity-impact tests on all metals used in components that are subject to failure from meteoroid impact. Test data shall be obtained for the highest possible impact velocities. The other test parameters shall be adjusted so that the response of the structure to the kinetic-energy distribution of meteoroids encountered in space can be determined.**

Radiation Damage. **When the degradation of material properties cannot be determined by analogy, comparison, or interpolation of data from previous tests, the materials shall be tested in radiation facilities that represent the projected service environment as nearly as practicable.**

For recommended practices applicable to solar electromagnetic radiation, refer to AFSC DH 3-2 (DN 4C3). For information on particulate radiation, refer to AFSC DH 3-2 (DN 4B4).

7.5 DEVELOPMENT TESTS

Development tests shall be performed as necessary to:

- **Evaluate design concepts**
- **Verify analytical techniques**
- **Evaluate structural modifications for achieving desirable structural characteristics**
- **Obtain data for reliability predictions**
- **Determine failure modes or causes of failure.**

For recommended practices, refer to NASA SP-8043.

7.6 QUALIFICATION TESTS

Qualification tests shall be conducted on flight-quality hardware to demonstrate structural adequacy under more stringent loads than the worst expected loads.

In defining the number and types of qualification tests, the highest practicable level of assembly shall be used. Test conditions shall be selected to demonstrate clearly that all elements of the structure satisfy the design criteria of Sections 4 and 5.

The test fixtures, support structure, and methods of environmental application shall not induce erroneous test conditions.

Support structure should be designed to simulate the flight-load distribution and stiffness of the vehicle at the support structure-specimen interface.

Instrumentation for qualification tests shall be coordinated with flight-test-vehicle instrumentation and shall be provided to measure all applied loads and environments and the response of the hardware. The instrumentation shall provide sufficient data to ensure proper application of the accept-reject criteria. The sequences, combinations, levels, and durations of loads and environments shall demonstrate that design requirements have been met.

For recommended practices, refer to NASA SP-8044.

Qualification should be accomplished by one of the following methods: (1) subjecting the components, assemblies, or systems to qualification tests; (2) basing qualification on tests conducted on similar configurations in a similar environment; (3) prior vehicle qualifications; (4) qualification of higher structural levels of assembly; or (5) basing the qualification on other tests or history, such as vendor tests, static firings, or flight tests. Hardware should be subjected to requalification tests when changes have been made in design or manufacturing processes which affect functioning or reliability; when inspection, test, or other information indicates that a more severe environment or operating condition exists than that for which the hardware was originally tested; or when hardware is made by a different company than previous similar hardware.

During tests, input parameters, system outputs, and structural response should be monitored continuously.

Anomalous behavior during tests and its potential influence on the vehicle should be identified.

7.6.1 STATIC TESTS

7.6.1.1 LIMIT CONDITIONS

Tests shall be conducted to verify that the general structure does not experience detrimental deformation at limit loads and pressures in accordance with the criteria of Sections 4 and 4.1.

Deformation of structural joints subjected to loads and elevated temperatures and to thermal stresses should be measured for all critical locations and conditions. An increased deflection of structure due to creep elongation of bolt holes should be evaluated by test. Cumulative strain measurements should be made of test assemblies during periodic disassembly and reassembly of fabricated structure.

7.6.1.2 ULTIMATE CONDITIONS

Tests shall be conducted to verify that the structure does not rupture or collapse at ultimate load and pressure in accordance with the criteria of Section 4.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8040, AFSC DH 3-2 (DN 4C3), FAA-FAR Part 25, MIL-A-8867(ASG), and ASD-TR-66-57.

7.6.1.3 COMBINED LOADS AND INTERNAL PRESSURE

Tests shall be conducted to verify the capability of the pressure vessels and pressurized structure to withstand without failure combined internal pressure and external forces in accordance with the criteria of Sections 4, 4.1.1, and 4.1.2.

When pressure combined with external forces is detrimental to structural stability or load-carrying capability, the ultimate pressure shall be combined with ultimate external forces in tests for strength and deformation. When pressure combined with external forces is beneficial to structural stability or load-carrying capability, the limit pressure shall be combined with ultimate design external forces in tests for strength and deformation.

For additional information, refer to NASA SP-8040, AFSC DH 3-2 (DN 4C3) and MIL-A-8867(ASG).

7.6.1.4 COMBINED LOADS AND THERMAL EFFECTS

Tests shall be conducted to verify the capability of the structure to withstand without detrimental deformation the combined loads at the expected operating temperatures.

Test loads and temperatures should be distributed in a manner representing actual service distributions as nearly as possible. Loading conditions may be simplified by modifying the load distributions in regions of structure not critical for the test condition or for structure identical in construction to other structure more highly stressed (by the same or other test conditions). Load simplifications which result in conditions of deformations or possible failures not met in mission conditions should be avoided. More than one loading condition may be applied simultaneously to different portions of the structure, providing interaction does not exceed the design load on any portion of the structure. Unaccountable effects, such as combined loads and material behavior, should be provided for in all test loads and procedures where such effects cannot be properly simulated. All prior load history affecting structural adequacy should be simulated.

For recommended practices, refer to NASA SP-8004, SP-8007, SP-8019, and SP-8045, AFSC DH 3-2 (DN 4C3), and MIL-A-8867(ASG).

7.6.1.5 ULTIMATE PRESSURE

At least one specimen typical of flight hardware shall be tested to demonstrate that each structure is capable of sustaining ultimate pressure without rupturing, in accordance with the criteria and comments of Section 4. Each test specimen shall be of the same design as planned for flight hardware and shall be fabricated from the same materials and by the same processes planned for production of flight hardware. The effects of operating temperatures and environments shall be accounted for in the tests.

7.6.2 STATIC-ELASTICITY TESTS

7.6.2.1 DIVERGENCE

It shall be demonstrated by wind-tunnel tests that the space vehicles are free of divergence under the conditions cited in Section 4.4.1 when this cannot be proven by analytical methods (i.e., when they are not available, not accurate, or not corroborated by experimental data).

The test specimens should be either dynamic models or full-scale components. If dynamic models are used, the adequacy of the simulation of the dynamics of the space vehicles should be verified by influence-coefficient, structural-stiffness, and/or vibration tests of all the full-scale space vehicles in the flight configuration.

For recommended practices, refer to NASA SP-8003, AFSC DH 3-2 (DN 4C7) FAA-FAR Part 25, and MIL-A-8870(ASG).

7.6.2.2 CONTROL-SURFACE REVERSAL

It shall be demonstrated by wind-tunnel tests that the vehicle is controllable at all points along the dispersed trajectory during flight within the atmosphere under the conditions cited in Section 4.4.2 when controllability cannot be shown by analytical methods (i.e., when they are not available, not accurate, or not corroborated by experimental data).

For recommended practices, refer to FAA-FAR Part 25, and MIL-A-8870(ASG).

7.6.2.3 BUCKLING AND CRIPPLING

Structures representative of flight hardware shall be tested under the conditions cited in Section 4.4.3. Tests shall be conducted simulating the compressive design loads when: (1) configurations are shells of arbitrary shape; (2) configurations are of minimum weight, and coupling between the various modes of failure is possible; (3) no theory or correlation factor exists; (4) correlation factors used are less conservative than those recommended in NASA SP-8007, SP-8019, and SP-8032; and (5) cutouts, joints, or other design irregularities occur.

For recommended practices, refer to MIL-A-8867(ASG) and NASA SP-8007, SP-8019, and SP-8032.

7.6.3 DYNAMIC AEROELASTIC-INSTABILITY TESTS

Tests shall be conducted as a supplement to analysis to verify freedom from undesirable axial-lateral coupling in accordance with the criteria of Section 4.5. Scaled dynamic and aeroelastic models shall be used, as appropriate.

7.6.3.1 CLASSICAL FLUTTER AND STALL FLUTTER

It shall be demonstrated by wind-tunnel tests that the space vehicles are free of flutter under the conditions cited in Sections 4.5.1.1 and 4.5.1.2 when analytical methods are not adequate (i.e., not available, not sufficiently accurate, or not corroborated by experimental data) or when the results of suitable analyses indicate marginal stability.

Test specimens should be either dynamic models or full-scale elements of the space vehicles. It should also be demonstrated by influence-coefficient, structural-stiffness, and/or vibration tests of full-size vehicles in the flight configuration that the scale models adequately simulate the dynamic characteristics of the space vehicles. Dynamic characteristics of the scale models should also reflect the variation in modulus of elasticity with the anticipated service temperatures.

For additional information, see NASA NHB 8080.1, NHB 8080.3, NASA SP-8003, AFSC DH 3-2 (DN 4C6), FAA-FAR Part 25, and MIL-A-8870(ASG).

7.6.3.2 PANEL FLUTTER

If test data do not exist for panels of similar structural configuration, edge-support conditions, and aerodynamic parameters, it shall be demonstrated by wind-tunnel tests on dynamically scaled models or full-scale components that external panels are free of panel flutter under the conditions of Section 4.5.1.3.

At least one panel of each structural type on the vehicles for which data do not exist should be tested at dynamic pressures up to 1.5 times the maximum local dynamic pressure expected to be encountered at any Mach number within the normal operating envelope. Thermally induced loads, mechanically applied loads, and pressure differentials across the panels should be simulated in the tests.

For additional information, refer to NASA SP-8004 and AFSC DH 3-2 (DN 4C6).

7.6.3.3 CONTROL-SURFACE BUZZ

It shall be demonstrated by wind-tunnel tests in the transonic speed range that the space vehicles are free of control-surface buzz under the conditions cited in Section 4.5.1.4.

The test specimens should be either dynamic models or full-scale components, and both Mach number and Reynolds number should be simulated in the tests. At least one flight-test vehicle should be instrumented to detect control-surface buzz in flight-test regions of greatest dynamic pressure.

For recommended practices, refer to NASA SP-8003.

7.6.4 DYNAMIC-COUPLING TESTS

Ground dynamic tests shall be conducted on representative vehicle structure in the mated and unmated configurations to assess compatibility of the flexible structures with functional systems.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8016, AFSC DH 3-2 (DN 4C7), ASD-TR-66-57, and MIL-A-8871(USAF).

7.6.4.1 CONTROL SYSTEM AND ELASTIC MODES

Ground tests shall be conducted as a supplement to analyses to demonstrate that the space vehicles are free of coupling between the control system and vehicle elastic modes in accordance with the criteria of Section 4.5.2.1.

Ground tests for this type of coupling should include testing of components, vibration testing of the structure, closed-loop simulation testing with as much flight hardware as possible included, and overall system tests, including both structure and control system.

For recommended practices, refer to NASA SP-8016.

7.6.4.2 SLOSH

Tests shall be conducted to verify the slosh-suppression analysis and the effectiveness of the slosh-suppression devices.

Reduced-scale-model tests, full-scale ground tests, or flight tests may be employed.

For recommended practices, refer to NASA SP-8009 and SP-8031.

7.6.4.3 STRUCTURE AND PROPULSION SYSTEM (POGO)

Analytical longitudinal dynamic models of the vehicles shall be verified by experiment.

For recommended practices, refer to the forthcoming NASA special publication on prevention of coupled structure-propulsion instability (pogo) and NASA SP-8036.

7.6.5 DYNAMICALLY INDUCED ENVIRONMENT TESTS

7.6.5.1 VIBRATION

Ground vibration tests shall be conducted to verify: (1) structural adequacy in the vibration environment; (2) predicted structural response to the vibration environment; (3) efficiency of vibration-isolation mounts and panels; and (4) proper damping and vibration-transmission characteristics.

Vibration fixtures shall be designed to avoid fixture-induced attenuation, amplification, or resonance within the range of test conditions.

Particular consideration should be given to structure supporting massive equipment or equipment sensitive to discrete frequency bands. Service environments should be closely simulated in ground vibration tests determining structural strength.

For recommended practices, refer to NASA SP-8043, SP-8044, FAA-FAR Part 25, and MIL-A-8870(ASG).

7.6.5.2 MODAL SURVEY

Ground dynamic tests shall be conducted on representative vehicle structure in the mated and unmated configurations to determine natural vibration-mode shapes, frequencies, amplitudes, and modal-damping characteristics. The modal surveys of the vehicles, including the mated configurations or major assemblies, as appropriate, shall be used to correlate with and confirm theoretical results obtained on mathematical models. Surveys shall be conducted at several weight conditions for each flight configuration, considering the effects of liquid expenditure, liquid sloshing, control-force application, programmed maneuvers, and engine thrust.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8009, SP-8012, SP-8016, SP-8036, ASD-TR-66-57, AFSC DH 3-2 (DN 4C7), MIL-A-8870(ASG), and MIL-A-8871 (USAF).

7.6.5.3 EQUIPMENT MOUNTS

Tests shall be conducted to verify that the equipment-support structure with the applicable item of equipment mounted will be adequate for the mission requirements.

Local resonances of the supporting structure should be determined to permit comparison with the resonances of the vehicle structure or equipment in close proximity.

For recommended practices, see NASA SP-8044. Additional information on equipment mounts is presented in AFSC DH 3-2 (DN 4B5).

7.6.5.4 ACOUSTIC

Acoustic tests shall be conducted to verify the adequacy of the structure to withstand the acoustic environment.

Particular consideration should be given to structure characterized by lightly stiffened surface areas and equipment susceptible to high-frequency excitation. Service environments and in-service boundary conditions

should be closely simulated on test specimens. Applicable tests on similar configurations may be utilized, subject to NASA approval.

For recommended practices, refer to AFSC DH 3-2 (DN 4C4).

7.6.5.5 SHOCK

Mechanical shock tests shall be conducted when analyses or previous tests on similar structure do not clearly demonstrate structural adequacy or adequately define structural response to nonexplosive mechanical shock to which the vehicle may be subjected.

Pretest documentation should show that the test input, model, instrumentation, and procedures will be sufficient to demonstrate structural adequacy for mechanical shock.

For recommended practices, refer to the forthcoming NASA special publication on structural vibration prediction.

Impact tests shall be conducted when analyses or related tests do not clearly demonstrate the adequacy of structure to withstand impact loads in combination with other design loads and environments.

Pretest documentation should show that the test boundary conditions are valid and that the test input, test specimen, mounting fixture, instrumentation, and procedures are appropriate. For additional information, refer to AFSC DH 3-2 (DN 4C3).

Explosive shock sources and responses, potential damage from explosive shock, and techniques to suppress and control damage shall be evaluated by tests if adequate analytical techniques are not available.

For additional information, refer to AFSC DH 3-2 (DN 4C1) and a forthcoming NASA special publication on protection against explosive shock.

Components and assemblies subject to possible dropping or tumbling shall be tested to the drop-test requirements of MIL-STD-810B. The shock levels transmitted to critical cushioned or packaged components shall be determined from rational analysis to verify that the protected components are not damaged.

7.6.5.6 GROUND WIND LOADS

Measurements of loads and motions induced by ground winds shall be made on the vehicle at the launch pad to establish the validity of wind-tunnel tests and analysis.

These measurements should include vehicle response, such as bending moment or accelerations, and simultaneous measurements of the frequency and damping of the relevant vibration modes of the vehicle on its launch pad.

For recommended practices, refer to AFSC DH 3-2 (DN 3A3) and NASA SP-8008.

7.6.6 THERMAL TESTS

7.6.6.1 STRUCTURAL TEMPERATURES

Full-scale tests shall be conducted to verify predicted structural temperatures. When the size of the structure makes it impractical to conduct full-scale ground tests or when heating conditions cannot be accurately represented in such tests, flight tests shall be employed. Any of these tests shall include high and low temperature extremes. Scatter in the test data shall be defined and deficiencies in the simulation of the operational environment shall be analyzed.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8014, SP-8029, SP-8040, ASFC DH 3-2 (DN 4C3), MIL-A-8860(ASG), ASD-TR-66-57, and a forthcoming NASA special publication on entry gasdynamic heating.

7.6.6.2 JOINT CONDUCTANCE

Tests shall be conducted to verify joint conductance.

For recommended practices, refer to NASA NHB 8080.1, NASA SP-8014, MIL-STD-470, and MIL-A-8867(ASG).

7.6.6.3 SURFACE THERMAL RADIATION PROPERTIES

Solar absorptance and infrared emittance shall be determined experimentally where necessary to ensure confidence in the thermal control of structure. No design factors are to be applied to the values obtained.

For recommended practices, refer to NASA SP-8014.

7.6.6.4 EXHAUST-PLUME IMPINGEMENT

The effects of exhaust-plume impingement from rocket motors on vehicle structure shall be experimentally determined, including the effects on skin and on radiation coatings or temperature-control surfaces.

For recommended practices, refer to NASA SP-8029.

7.6.6.5 THERMAL BUCKLING OF PANELS

The effects of rapid rates of heating on the buckling strength of stiffened panel construction shall be determined by test.

Thermal stresses interacting with load stresses for both uniform and nonuniform heating can have significant effects in reducing the buckling load of structure. Depending upon the mode of buckling, the thermal stresses may or may not affect the magnitude of the maximum load.

For recommended practices, refer to NASA SP-8044 and AFSC DH 3-2 (DN 4C3).

7.6.6.6 THERMAL PROTECTION SYSTEMS

Thermal tests shall be conducted to verify the analyses employed for each design heating condition up to the most severe anticipated heating environment. Physical and thermal adequacy shall be demonstrated under the simulated operating environments, both for high-temperature and low-temperature applications.

Frequently, tests cannot be performed in a completely simulated flight environment. Transient effects, for example, are frequently important during the period of maximum flight heating, but test conditions duplicating the extremes of the flight environment can usually be achieved only as steady states. It is therefore often desirable to try to duplicate the predicted total heat input by various combinations of heating rates and exposure times. In this manner, the transient effects of char formation on the ablative material can be at least partially simulated. If the test models are instrumented with thermocouples and the measured temperature histories, and the mass loss and surface recession are analytically matched, much insight can be gained into the material properties and the analytical model.

For additional information, refer to NASA SP-8014.

7.6.6.7 INSULATION

Tests shall be conducted to demonstrate the thermal and structural adequacy of insulation systems under repetitive cycles of the heating or cooling expected throughout the service life.

For recommended practices, refer to NASA SP-8044 and AFSC DH 3-2 (DN 4C3).

7.6.7 LIFE TESTS

7.6.7.1 SAFE-LIFE

Safe-life tests shall be conducted for structural components and assemblies that have little or no tolerance for damage during operation in accordance with the criteria of Section 4.8.

The fatigue-test life with appropriate reduction factors for inherent structural scatter in behavior may be used to establish the safe-life of components such as pressure vessels and landing gears.

For safe-life design concepts utilizing the proof test as the final inspection, the amount and type of preproof nondestructive inspection (NDI) required should be determined considering the impact of a proof-test failure on vehicle and program costs and schedules.

For safe-life design concepts which depend on NDI for structural life assurance, it should be demonstrated that the techniques are adequate to ensure detection of significant defects.

The more important defects for which inspection techniques should be defined are noted in Section 4.7.3.

7.6.7.2 FAIL-SAFE

Fail-safe tests shall be conducted in accordance with the criteria of Sections 4.8.2 through 4.8.7 to demonstrate structural tolerance to damage and the residual load-carrying ability at the specified percentage of limit loads for critical structure (excluding structure for which safe-life is applicable, such as metallic pressure vessels and landing gears).

Fail-safe tests may be conducted either on structure containing cracks in a single component developed during fatigue testing or on structure which has been purposely cut to simulate accidental severance of members.

During these tests, the load applied to the structure should not be greater than the specified fail-safe load.

7.6.7.3 MATERIAL PROPERTIES

Material properties affecting the prediction of life shall be determined in accordance with the criteria of Section 4.8.3.

7.6.7.4 CYCLIC LOADS

Cyclic load tests shall be performed in accordance with the criteria of Section 4.8.5.

The test-loading conditions, environments, and stress states, and their distribution and combinations shall represent as accurately as possible those expected during the service life of the structure.

For recommended practices, refer to MIL-A-8867(ASG), FAA-FAR Part 25, ASD-TR-66-57, and AFSC DH 3-2 (DN 4B2).

For some conditions, the behavior of structural components may be determined from tests of simple coupons containing various geometric stress concentrations.

For metallic pressure vessels, data on flaw growth due to cyclic loading shall be obtained for parent metal, weldments, and heat-affected zones by subjecting preflawed components to tests which simulate the anticipated service loads, environments, and temperatures, and their variations with time.

For recommended practices, refer to NASA SP-8040.

7.6.7.5 SUSTAINED LOADS

Sustained-load tests shall be performed in accordance with the criteria of Section 4.8.6.

7.6.8 INTERFACE-COMPATIBILITY TESTS

It shall be demonstrated that the vehicle structure is physically and mechanically compatible with functional components, assemblies, systems, fluids, and gases. As a minimum, the tests shall verify that the conditions and structural interactions identified in Section 4.9 have been adequately accounted for in design. Tests shall be conducted under environmental conditions suitable to permit proper assessment of interactions.

Tests shall be conducted to verify that structural materials are compatible with all liquids and gases employed in the vehicle.

The performance of lubricants shall be determined by tests in the simulated service environment.

Refer to Section 4.7.11 for additional criteria on lubricant characteristics. For recommended practices, refer to NASA NHB 8080.1, NASA NHB 8080.3, and MIL-A-8867(ASG).

7.6.8.1 LEAKAGE

Leakage rates shall be determined in accordance with the criteria of Section 4.10.3 for structural joints, seals, access hatches, skin penetrations, and pressure fittings.

For additional information on leakage testing, refer to NASA TN D-5864.

7.6.8.2 VENTING

Tests shall supplement analysis as may be necessary to verify the adequacy of compartment-venting provisions in accordance with the criteria of Section 4.10.4. The largest practicable assemblies shall be employed in the tests.

7.6.8.3 MECHANICAL COMPONENTS

7.6.8.3.1 DOORS AND WINDOWS

The structural integrity of doors and windows under ultimate conditions of load and pressure shall be demonstrated in accordance with the criteria of Section 4.10.5.

7.6.8.3.2 MISALIGNMENTS AND TOLERANCES

Tests shall be conducted to verify that specified structural and functional characteristics are not violated by allowable accumulated misalignments and dimensional tolerances.

7.6.8.4 DEPLOYABLE AERODYNAMIC DECELERATORS

Tests shall be conducted on deployable aerodynamic decelerator systems in accordance with the criteria of Section 4.10.6 to verify the structural integrity of components and analytical models used in design calculations of the system. Physical characteristics and mechanical properties of fabrics shall be verified by aerial deployment tests under more severe conditions of dynamic pressure and velocity than anticipated, and approximating ultimate load conditions as closely as possible.

The following characteristics shall be evaluated: (1) ultimate strength and elongation; (2) tear resistance and tear-stop characteristics; (3) fabric porosity; (4) resistance to aerodynamic heating; (5) compressibility effects; and (6) opening shock loads and transients.

For recommended practices, see the forthcoming NASA special publication on deployable aerodynamic deceleration systems.

7.6.8.5 METEOROID PROTECTION

Tests shall be conducted on the meteoroid shield in accordance with the criteria of Section 4.10.7 to demonstrate the capability of the shield to sustain impacts by projectiles having the same kinetic-energy distributions as meteoroids in space, without damaging the shield structure beyond prescribed limits or degrading the function of other vehicle systems.

Test specimens shall have the same geometry, material, temperature, and stress level as the structural component being represented. Test data shall be obtained for the highest possible impact velocities.

For recommended practices, refer to NASA SP-8042.

7.6.8.6 CRASHWORTHINESS AND DITCHING

Tests shall be conducted to verify analytical predictions of crashworthiness characteristics in accordance with the criteria of Section 4.10.9. Scale-model tests may be used to evaluate ditching characteristics in lieu of full-scale tests.

7.6.8.7 ANTENNAS

Tests shall be conducted to verify the mechanical and functional performance of antennas and their deployment or aiming mechanisms in accordance with the criteria of Section 4.10.10.

7.6.8.8 CASTINGS

Each casting design shall be tested in accordance with the criteria of Sections 4.1 and 4.10.11 to demonstrate structural integrity for ultimate and limit loads, both at critical temperature conditions.

7.6.8.9 FRICTION AND WEAR

Tests shall be conducted on all contacting surfaces designed to undergo sliding or rolling motion in accordance with the criteria of Section 4.10.12. These tests shall show that the friction and wear characteristics are acceptable and in agreement with analytical predictions. Service-life usage, environment, and chronological sequence shall be simulated as realistically as possible in the tests. All variables that affect friction and wear shall be controlled, including vacuum, temperature, load, speed, cyclic behavior, material hardness and topography, and atmospheric pressure and composition. Use of mechanisms during test and checkout shall be accounted for.

7.6.8.10 NATURAL AND MAN-MADE ENVIRONMENTS

Tests shall be conducted to demonstrate that the vehicle structure is capable of withstanding, or that it is protected from, the effects of the natural and man-made environments identified in Sections 5.1.3 and 6.

7.7 ACCEPTANCE TESTS

Tests shall be conducted on flight hardware to verify that the materials, manufacturing processes, and workmanship meet design specifications. When verification cannot be obtained by in-process tests, component and assembly tests shall be conducted to verify that the structure has been manufactured to meet design requirements. Unless definite verification can be obtained by lower-level tests, full-system tests shall be conducted to verify the adequacy of the complete structure. The test loads shall not exceed the limit loads, except in pressure-proof tests.

Support structure should be designed to simulate flight-load distributions and the stiffness of the vehicle at the support structure-specimen interface. Captive firing, handling, and transport loads should also be accounted for. The hardware should not be significantly fatigued by acceptance testing so as to impair its service life.

Anomalous behavior during tests and its potential influence on the vehicle should be identified.

For recommended practices, refer to NASA SP-8045.

7.7.1 MISALIGNMENTS AND TOLERANCES

It shall be verified by in-process measurements and inspections that alignments and dimensional tolerances are within prescribed limits.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8045, and NASA NPC 200-2.

7.7.2 THERMAL PROTECTION SYSTEMS

Materials used in the thermal protection system (including surface coatings) shall be shown by test measurements to possess the thermal properties and other characteristics assumed in the design calculations.

Both before and during manufacture of the thermal protection system, several steps should be taken to ensure that the flight hardware will possess the same properties obtained in laboratory or model-shop fabrication and used in the design calculations. The first step is to establish firm specifications for material procurement and processing. Following this, all steps in the manufacturing and assembly process should be reviewed with quality-control and inspection personnel to ensure that inspections will be performed and accurate records maintained of all pertinent properties and measurements.

7.7.3 PRESSURE VESSELS

All pressure vessels and pressurized structure intended for flight use shall be proof tested in accordance with the criteria of Sections 4 and 4.1.

Pressure vessels and main propellant tanks shall be tested at proof pressures.

When it has been shown by test that the pressure-vessel materials exhibit a decreasing resistance to fracture with decreasing temperature, the proof test shall be conducted at a temperature equal to or below the lowest expected operating temperature.

The time for pressurization to the proof-pressure level and the time the pressure is sustained at that level shall be held to the minimum consistent with test-system limitations. Depressurization time shall also be held to a minimum.

Tests shall be conducted to verify that the probable failure mode in service will be leakage rather than catastrophic fracture when assurance of safe-life cannot be provided by proof test.

For recommended practices, refer to NASA SP-8040.

7.7.4 CASTINGS

All castings intended for flight use shall be proof tested to limit loads at critical temperature conditions in accordance with the criteria of Sections 4.1 and 4.10.11.

For recommended practices, refer to MIL-A-8860(ASG).

7.7.5 LEAKAGE

Tests shall be conducted on pressurized structure in accordance with the criteria of Section 4.10.3 to measure the leakage rate and to verify that leakage is within prescribed tolerances.

7.7.6 MECHANISMS

Tests shall be conducted to verify that all mechanisms operate within prescribed tolerances.

7.7.7 DOORS AND WINDOWS

Functional tests shall be conducted to verify that doors, movable covers, and their actuating mechanisms, locks, and related items of mechanical equipment operate within prescribed tolerances.

7.7.8 RECEIVING AND IN-PROCESS INSPECTION

Receiving tests, in-process tests, environmental tests, and inspections shall be conducted to ensure that manufacturing processes and workmanship comply with prescribed design characteristics (Sec. 4) and procurement specifications.

For recommended practices, refer to NASA NHB 8080.1, NHB 8080.3, NASA SP-8040, and SP-8045.

7.8 FLIGHT TESTS

Flight tests shall be conducted to provide adequate confidence in the limit loads used in the design and in the test conditions used in the qualification tests.

At least one flight test shall be instrumented to collect data permitting an evaluation of each of the following:

- **Flutter in the region of greatest dynamic pressure and most severe heating**
- **Control-surface buzz in the region of greatest dynamic pressure**
- **Buffeting**
- **Elastic-mode coupling of structure and propulsion system (pogo)**
- **Control-system elastic-mode coupling**
- **Fuel-slosh coupling**
- **Axial-lateral coupling**
- **Structural response to explosive shock**
- **Refurbishment techniques**
- **Heating.**

These flight tests should be closely integrated with the

structural development and qualification tests and with flight tests for validation of other systems. Anomalous behavior during tests should be identified and its potential influence on the vehicle should be determined.

For recommended practices on flight-loads measurements, refer to NASA SP-8002.

7.9 SPECIAL TESTS

7.9.1 RELIABILITY

Useful life shall be verified by reliability tests.

For recommended practices, refer to NASA NHB 5300.4(1A), NHB 8080.1, NHB 8080.3, NASA SP-8043, SP-8044, and MIL-STD-785A.

Overstress tests shall be conducted to determine failure modes, failure rates, and safety margins of major structural assemblies.

For recommended practices, refer to NASA NHB 5300.4(1A), NASA NHB 8080.1, NHB 8080.3, NASA SP-8044, AFSC DH 3-2, and MIL-STD-785A.

Receiving tests, in-process tests, environmental tests, and inspections shall be conducted to verify production hardware reliability.

For recommended practices, refer to NASA NHB 5300.4(1A), NHB 8080.1, NHB 8080.3, NASA SP-8045, and MIL-STD-785A.

Reliability of processes and standards shall be verified by test.

For recommended practices, refer to NASA NHB 8080.1 and NHB 8080.3.

7.9.2 MAINTAINABILITY

Maintainability tests shall be integrated with qualification and acceptance tests and shall include tests for access and servicing, interchangeability, fault detection, repair, and replacement.

For recommended practices, refer to NASA NHB 8080.3 and MIL-STD-470.

7.9.3 INSPECTION

Techniques for inspection of vehicle structure shall be developed to locate hidden defects, deteriorations, and fatigue effects.

Nondestructive inspection techniques are not adequate for all purposes. Tables 7-1, 7-2, and 7-3 list available techniques for inspection of coated refractory alloys, ceramics, and composites, respectively, with an indication of their current practical applicability in the field.

TABLE 7-1 **NONDESTRUCTIVE INSPECTION OF COATED REFRACTORY ALLOYS**

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Visual	Coating defects		X	Very noticeable metal oxide
Dye penetrant	Cracks, holes	X		Possible contamination
Thermoelectric	Coating thickness	X	X	Slow; exterior surface only
Eddy current	Coating thickness	X	X	Slow; exterior surface only
X-ray backscatter	Coating uniformity	X		Applicable to simple shapes
Ultrasonic	Honeycomb bonds	X		Well developed
Radiograph	Fabrication defects	X		Well developed
Scintillators	Coating thickness	X	X	Requires radioactive substance in coating material; requires development

TABLE 7-2 **NONDESTRUCTIVE INSPECTION OF CERAMICS**

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Dye penetrant	Cracks	X		Possible surface contamination
Sonic	Cracks	X	X	Well developed
Ultrasonic	Cracks	X		Well developed
Thermal	Uniformity	X		Infrared mapping required

TABLE 7-3 **NONDESTRUCTIVE INSPECTION OF COMPOSITES**

TECHNIQUE	INSPECTION FOR	APPLICABLE TO		REMARKS
		FACTORY	FIELD	
Resin matrix				
Sonic	Debonding, voids, cracks	X	X	Well developed
Ultrasonic	Debonding, voids, cracks	X		Well developed
Radiography	Uniformity, voids	X	X	Well developed
Dielectric	Moisture	X	X	Principle developed
Resistivity	Moisture	X	X	Principle developed
Microwave	Resin cure	X		Frequency response is unknown; complex equipment required
Thermal	Uniformity	X		Infrared mapping required
Metal matrix				
Sonic	Debonding, voids, cracks	X	X	Principle developed
Ultrasonic	Debonding, voids, cracks	X		Principle developed
Radiography	Uniformity, voids	X	X	Difficult in field
Thermal	Uniformity	X		Infrared mapping required

7.9.4 OPERATIONAL USAGE MEASUREMENTS

Measurements of loads and temperatures during vehicle operation shall be taken to: (1) enhance confidence in predicted loads and temperatures; (2) reevaluate service-life expectancy; (3) evaluate intervals between inspections, refurbishments, and repairs; (4) establish operational limitations; and (5) provide data for development of improved structural design practices. Measurements shall be made at fatigue-critical or thermal-critical points on each vehicle.

Location of fatigue-critical and thermal-critical points should be established on the basis of all prior development, qualification, acceptance, and flight-test results.

For recommended practices on flight-loads measurements, refer to NASA SP-8002.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

U.S. CUSTOMARY UNIT	CONVERSION FACTOR*	SI UNIT
foot	0.3048	meter
inch	0.0254	meter
psf (pounds/foot^2)	47.8803	newton/meter^2
psi (pounds/inch^2)	6894.757	newton/meter^2
pound force	4.448	newton
mph (miles per hour)	0.447	meter/second

*Multiply value given in U.S. customary unit by conversion factor to obtain equivalent value in SI unit.

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